SECTION 3
INTERFERENCE TO PROFILERS

3.1 INTRODUCTION

Given the information in Section 2, the effect of interference on profiler performance can be estimated. This requires a characterization of the interfering source in terms of its power level, distance, frequency spectrum, time dependence, etc. Sources of interference fall into two general categories: coherent and incoherent.

This section discusses coherent and incoherent interference, system noise temperature, system frequency response, system noise power, and minimum detectable signal power. In addition, an interference analysis discussion is provided on the effects of frequency modulation (FM) and pulse type emissions on the wind profiler.

3.2 COHERENT INTERFERENCE

Coherent interference is potentially the most disruptive to profiler operation. This is because, by definition, a coherent interfering signal will be interpreted by the profiler as a valid signal in its Doppler spectrum. If the interfering signal is larger than the atmospheric return, it will be selected in the spectral moment calculations. If the signal frequency remained stable over the 1-minute dwell time for a beam and mode, it would be reported as the estimate of the radial velocity for that time period. Further, if the signal remained stable over a 1-hour period, then the erroneous Doppler velocity would pass consensus and form an erroneous indication of wind velocity.

Fortunately, the profiler has some built-in immunity to external stable signal sources. As explained in Section 2.5, the profiler controller/processor applies a pseudorandom phase shift sequence in order to reduce range-ambiguous returns. Since the phase-shifted signal is used to generate both the transmitted pulse and the receiver LO, the radar maintains internal coherence throughout the averaging process. External stable signals, such as ground returns from distances greater than the PRT-determined unambiguous range, are reduced in the averaging process. One other effect of this phase shift is to "whiten" any external, stable (CW) sources of interference. For an external system to remain truly coherent, it would have to detect the phase of the profiler pulse and shift its phase accordingly. Short of a sophisticated and intentional jamming effort, the probability of a truly coherent interfering signal is very small. The phase code cancellation is not perfect. On average, it provides about 20 dB of reduction. The effect of the pseudorandom coding is to place even highly stable real-world signals, such as data or voice FM signals, into the second category of interference.

3.3 INCOHERENT INTERFERENCE (NOISE)

Any interfering signal that is whitened by the phase code or any source of broadband noise will raise the system noise level, thereby degrading the system S/N. The effect of the added noise on profiler operation is to reduce the height coverage of the radar. However, it must be emphasized that there is no simple rule that can be used to determine that on any particular day a particular noise level increase will decrease the height coverage by some value.

The reason is the high dynamic range of the turbulence that accounts for the profiler radar returns. The turbulence structure parameter, C_n^2, may vary by 20 dB daily and 20 dB annually. The profilers have been designed with enough sensitivity to provide their designed height coverage most of the time. However, due to the variable nature of the returns there will be times when the profiler is unable to measure the winds at certain heights. At other times, the signals from all heights are strong enough that a S/N degradation on the order of 3 dB may not result in any loss of wind velocity measurements, although the uncertainty of the wind estimates may increase.

Based on analysis from years of profiler data, there has emerged a simple rule of thumb for the decrease in C_n^2 versus height.[4] It is generally accepted that it falls off at 1 to 2 dB per kilometer in the atmosphere above the boundary layer, which is typically 1 km. Therefore, one may state that, on average, an increase of x dB of system noise will result in about x/2 to x km loss in profiler height coverage. The lost wind data may not be at the highest gates since the lowest atmospheric turbulence sometimes occurs in layers that are sampled by the middle group of range gates. For example, the uniform winds in the jet stream at about 12 km altitude often lack the turbulence required to produce strong profiler radar returns. Under these conditions, the profiler may be operating at the limits of its signal detection capability. Any degradation in the S/N would result in lost wind estimates for the center of the jet stream while the enhanced turbulence above and below the jet stream would allow for normal wind measurements.

For the purposes of this analysis, we calculate the interference levels necessary to degrade the profiler system S/N by nearly 1 dB. An interference power level equal to 0.25 of the system noise power corresponds to an interference-to-noise ratio (I/N) of -6 dB which results in nearly 1 dB S/N degradation. We do not claim that this is an acceptable level of interference. Under some atmospheric conditions this level of interference could degrade the profiler height coverage from 0.5 to 1 km and may not be acceptable to the owner of the profiler. However, given the techniques outlined here and using a suitable model for propagation loss, one may calculate interference levels or separation distances for various interference sources for an assumed I/N.

3.4 SYSTEM NOISE TEMPERATURE

The profiler system operating temperature in degrees Kelvin, referenced to the antenna terminals, is[5]

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4 Nastrom, G.D., Gage, K.S., Ecklund, S.L., Variability of Turbulence, 4--20km, in Colorado and Alaska from MST Radar Observations, J. Geophys. Res. Vol. 91, 1986.

5 Skolnik, H.I., Radar Handbook, 1970, McGraw-Hill, Inc.

$$T_{sys} = \frac{T_{sky}\left(1-\frac{T_g}{T_{tg}}\right)+T_g}{l_a} + T_{ta}\left(1-\frac{1}{l_a}\right) + T_{tl}\left(l_l - 1\right) + l_l T_r\,, \qquad \textbf{(4)}$$

where

- T_{sys} = the system operating temperature
- T_{sky} = the cosmic sky noise temperature
- T_g = the effective ground temperature through sidelobes
- T_{tg} = the thermal ground temperature
- T_{ta} = the thermal antenna temperature
- T_{tl} = the thermal transmission line temperature
- T_r = the receiver noise temperature
- l_a = the antenna losses ($l_a > 1$)
- l_l = the transmission line losses ($l_l > 1$).

The factor T_g accounts for thermal ground noise entering through sidelobes. The contribution from thermal sky noise, T_{sky}, must then be reduced by T_g/T_{tg} and both of these terms are reduced by the ohmic losses, l_a, of the antenna. Since the sidelobes near the horizon of the profiler antenna have been measured at -25 dBi (discussed in Section 4.5), the contribution from the ground will not be used explicitly but, rather, will be factored in as an uncertainty. For the profiler network in the central United States, the cosmic noise temperature at 404 MHz in a 5° beam ranges from a low of 14° K near the galactic pole to about 70° K at the galactic equator.[6] There are also a few strong radio sources, notably Cassiopeia A at about 200° K and Cygnus A at about 175° K. Using 290° K for the physical temperatures T_{tg}, T_{ta}, and T_{tl}, a receiver noise figure of 0.53 dB (T_r = 37° K), and the measured or estimated antenna and transmission line losses of 1.26 (1 dB) each, the approximate range of system noise temperature is

$$200 < T_{sys} < 240 \quad °K \qquad \textbf{(5)}$$

or $$T_{sys} = 220 \pm 20 \quad °K \qquad \textbf{(6)}$$

with a few peaks from the radio sources.

[6] Recommendations and Report of the CCIR, 1986, Volume V, Propagation in Non-ionized Media.

3.5 SYSTEM FREQUENCY RESPONSE

The system frequency response is required to calculate the system noise power level. As mentioned in Section 2.6, the TDA process is used to reduce the data rate and also acts as a filter.[7] The profiler samples the received returns at a period equal to the PRT. It then coherently averages a number of these samples to form an input sample to the 128-point FFT. The resulting 128 complex spectral samples are weighted with a Hanning window in the frequency domain.[8] The frequency response of the coherent averager is

$$H(j\omega) = \exp[-j(M-1)(\omega\tau_0/2)]\frac{\sin(M\omega\tau_0/2)}{M\sin(\omega\tau_0/2)}, \quad \textbf{(7)}$$

where

ω = $2\pi f$ is the angular frequency (rad s^{-1})
M = the number of coherent averages (NTDA)
τ_0 = the sample period, which equals the PRT(s).

Four different filter functions correspond to the four unique combinations of coherent averages and PRTs listed in Table 2-1. The filter is pulse repetition frequency (PRF) periodic, so the frequency response is a comb filter that repeats the low-pass filter function at PRF = 1/PRT. Figure 3-1 shows the frequency response of the coherent averager for the oblique high mode ± 300 Hz around zero Doppler frequency, f_0. The response is -3.9 dB at the ± maximum Doppler frequency, sometimes referred to as the "foldover" frequency, and the first sidelobe level is -13.3 dB. Figure 3-2 shows the same oblique high mode response ± 7 kHz from f_0 and illustrates the PRF-periodicity (6472 Hz for oblique high). The maximum attenuation of the filter, discounting the nulls in the filter function, occurs at odd multiples of PRF/2 and reaches a level of M^{-1} (-34.3 dB for oblique high mode).

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7 Schmidt, G., Ruster, R. and Czechowsky, P., Complementary Code and Digital Filtering for Detection of Weak VHF Radar Signals from the Mesosphere. IEEE Trans. on Geoscience Electronics, *No.4,* October 1979.

8 Harris, F.J., On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform, Proc. IEEE, *No.1,* January 1978.

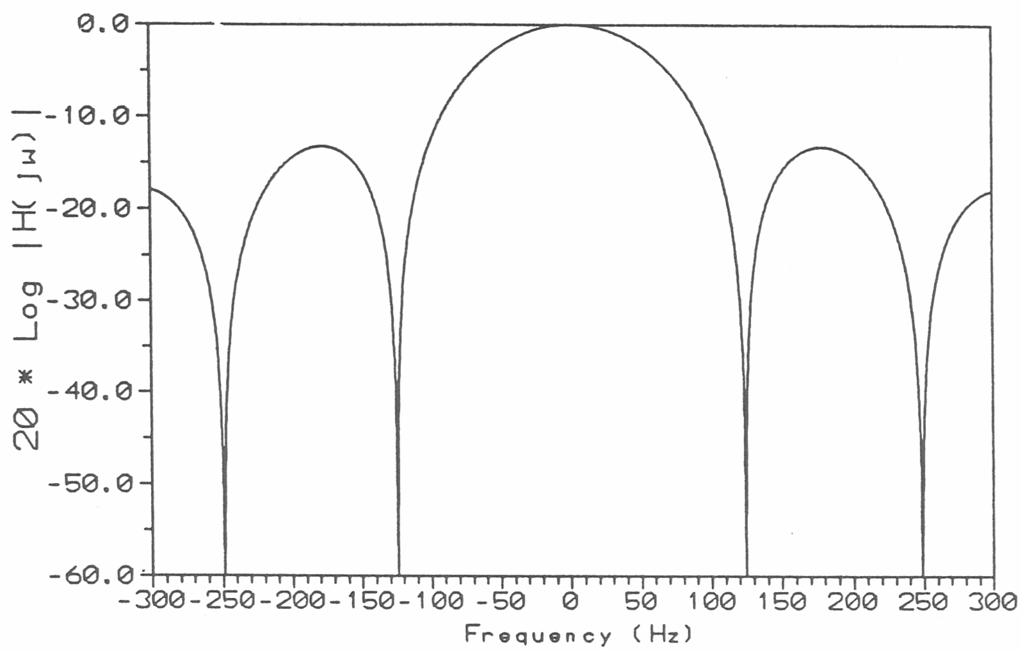

Figure 3-1. Oblique high mode TDA frequency response (± 300 Hz).

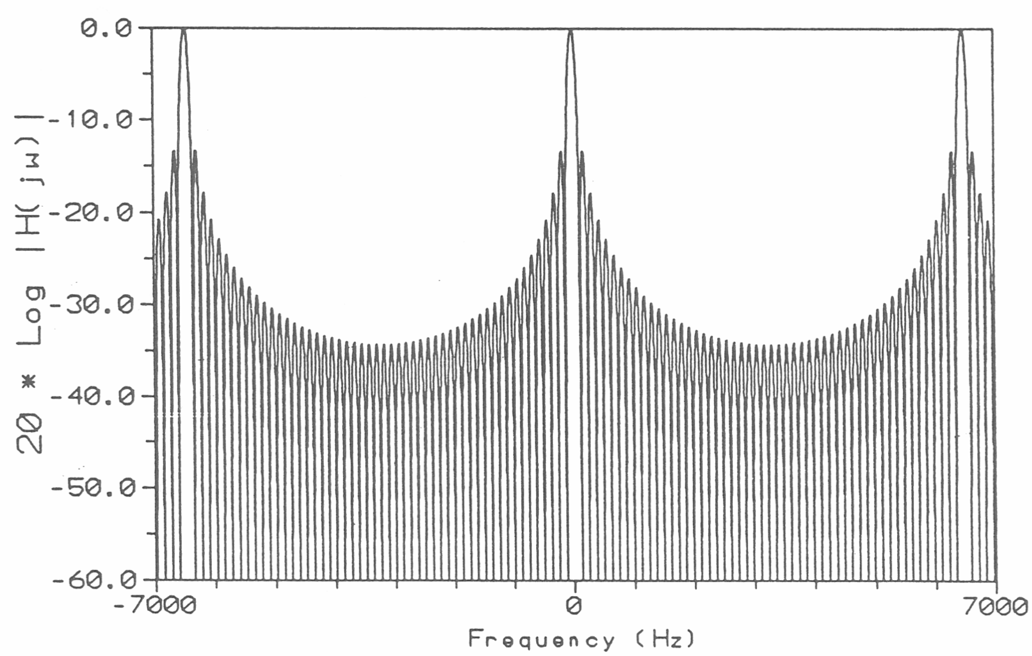

Figure 3-2. Oblique high mode frequency response (± 7000 Hz).

The Nyquist interval for the Doppler spectrum is $(\tau_0\ M)_{-1}$, which is PRF/M. Figure 3-2 illustrates that the coherent averager reduces the noise bandwidth by an amount proportional to the number of coherent averages. The corresponding statistical explanation is that coherently averaging a signal in the presence of noise improves the S/N by an amount equal to the number of averages (provided the signal maintains coherence over the averaging period).

Prior to the coherent averaging process, the intermediate frequency (IF) filters described in Section 2.5 determine the receiver frequency response. Since the coherent averaging is in series with the IF filter and ahead of the detector (the power spectrum calculated from the FFT), the pre-detection system frequency response is the product of the two. The system responses for the oblique high and oblique low modes are shown in Figures 3-3 and 3-4. The vertical beam responses are similar. These are the responses that must be used in the calculation of system noise levels or in the analysis of interference from other sources.

3.6 SYSTEM POST-PROCESSING NOISE POWER

The system post-processing noise power is

$$P_n = k\ T_{sys}\ B_{ef} = k\ T_{sys}\ \frac{B_{if}}{NTDA} \qquad \textbf{(8)}$$

where

P_n = the noise power (W)
k = Boltzmann's constant, 1.38×10^{-23} ($J\ K^{-1}$)
T_{sys} = the system noise temperature (K)
B_{ef} = the effective noise bandwidth (Hz)
B_{if} = the receiver IF bandwidth (Hz)
NTDA = the number of TDA.

The effective noise bandwidth in the equation is the integral of the response functions of Figures 3-3 and 3-4. Alternatively, one may simply divide the IF bandwidth by the number of coherent averages, to achieve identical results.

3.7 MINIMUM DETECTABLE SIGNAL POWER

The smallest signal detectable by the profiler has power just equal to the standard deviation in the noise power spectral density. In terms of the radar parameters of Table 2-1 and the system noise power defined above, the minimum detectable signal power is

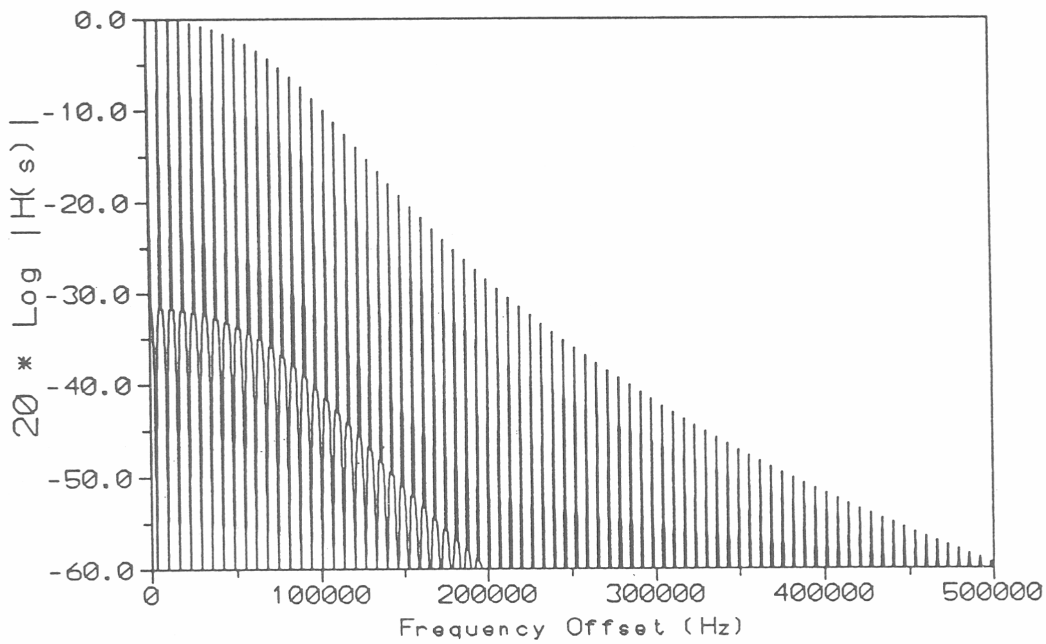

Figure 3-3. Oblique high mode frequency response.

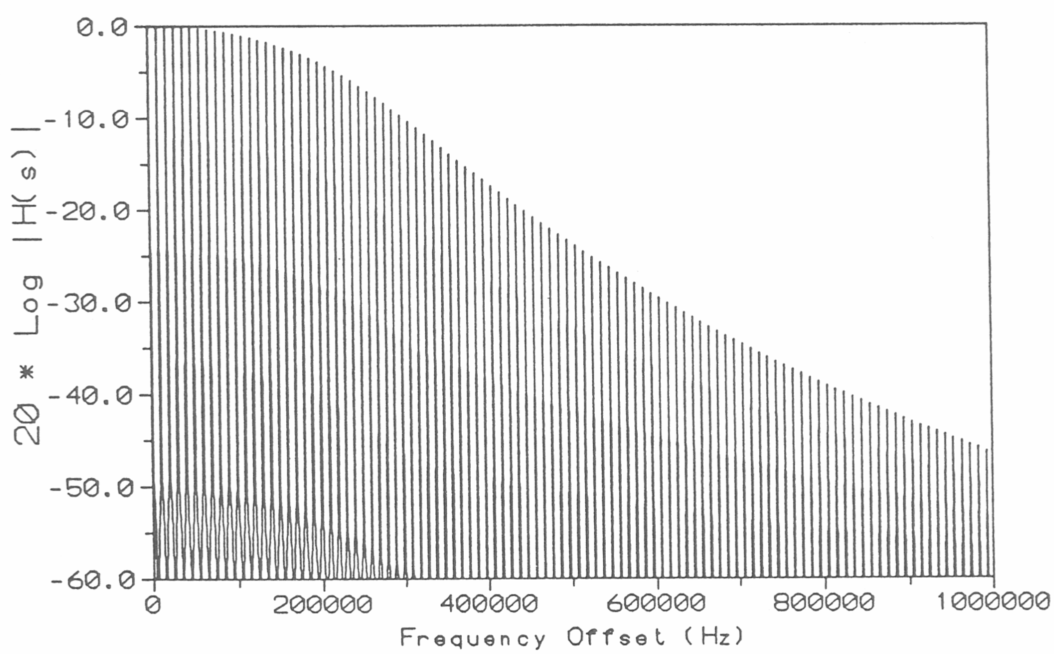

Figure 3-4. Oblique low mode frequency response.

$$S_{P_{m\ln}} = \frac{k\, T_{sys}\; B_{if}}{NTDA\; NFFT \sqrt{NSA}} = \frac{P_n}{128\,\sqrt{NSA}}\,, \qquad \textbf{(9)}$$

where

NFFT = the number of FFT points (128)
NSA = the number of incoherent spectral averages.

Table 3-1 lists the values from the above discussion for the different profiler modes. The low values for the system noise and the minimum detectable signal levels are the result of careful attention in the design of low-loss antenna and feed lines, a low-noise receiver, and the coherent and, to a lesser degree, incoherent averaging. The values are computed using the average value of system noise temperature described in Section 3.4.

TABLE 3-1
SIGNAL PROCESSING CHARACTERISTICS

	Low Mode		High Mode	
	Vertical	Oblique	Vertical	Oblique
Pulse repetition time (μs)	96.667	100.694	148.333	154.514
Pulse rep. frequency (Hz)	10345.8	9931.1	6741.6	6471.9
Coherent averages (NTDA)	152	118	100	52
Incoherent averages (NSA)	30	39	30	57
Max. ± Doppler freq. (Hz)	34.03	42.08	33.71	62.23
Dig. filter noise bandwidth (Hz)	68.1	84.2	67.4	124.5
Receiver IF bandwidth (kHz)	350	350	120	120
System noise bandwidth (Hz)	2303	2966	1200	2308
System noise power (dBm)	-141.6	-140.5	-140.4	-141.5
Min. detectable signal (dBm)	-170.0	-1695	-172.8	-171.4

3.8 INTERFERENCE ANALYSIS

The above discussions provide the information required to predict the effect of an interfering signal on the profiler. We emphasize again that **any** increase in the system noise level due to an interfering signal will degrade the profiler wind estimates. Whether the interference results in lost profiler height coverage depends on the highly variable atmospheric signals and cannot be determined *a priori.* However, using the 1-2 dB per kilometer rule of thumb discussed in Section 3.3, one can estimate the loss of height coverage for a particular interference level. We analyze the interference level referenced to the receiver input for typical FM and pulsed type interference since these types of signals are representative of systems operating in the band.

On-Tune FM

Figure 3-5 shows an assumed frequency spectrum for a voice-grade, FM signal centered at the same frequency as the profiler. It is shown imposed on the ± 15 kHz, oblique high mode profiler frequency response. For this analysis, the FM signal is assumed to have nearly uniform power density over the bandwidth of 16 (± 8) kHz, a modulation rate of 1 kHz, and a total power level of P_i dBm at the input to the profiler receiver. Since the 1-ms modulation period is much smaller than the profiler dwell time, we can use a power density of (P_i - 42) dBm/Hz over the 16 kHz FM bandwidth.

The total interference power is the product of the profiler frequency response with the FM signal power spectrum. Figure 3-5 shows that the most significant contribution to this product is from the profiler passbands near the center frequency and at the repetition frequency. So, as an approximation, one can use three times the filter noise bandwidth from Table 3-1 for the profiler frequency bandwidth. Then, for the oblique high mode, the total interference power is the power density times the noise bandwidth (3 x 124.5 Hz) or (P_i - 42.0 + 25.7) dBm.

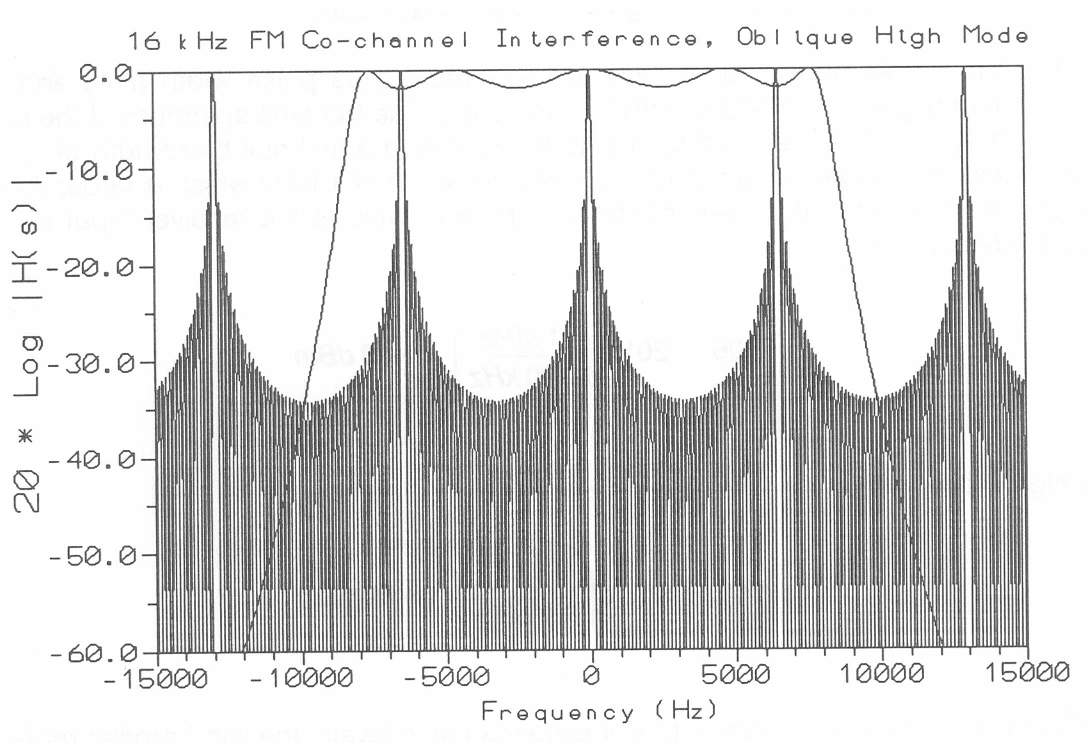

Figure 3-5. On-Tune FM interference.

Using the system noise levels for the four modes in Table 3-1, the average FM power levels required for an I/N of -6 dB are calculated using the following formula [(system noise power (dBm)) + 16.3 - 6]

oblique high	-131.2 dBm
oblique low	-130.2 dBm
vertical high	-130.1 dBm
vertical low	-131.2 dBm.

Off-Tune FM

If the same FM signal operated at a center frequency 1 MHz away from the profiler center frequency, Figure 2-4 shows that the low-mode and high-mode IF filters provide more than 45 dB and 80 dB of rejection, respectively. Therefore, interference signal levels at the receiver input of -85 dBm for the low mode, and -55 dBm for the high mode are required for an I/N of -6 dB. This type of off-tune analysis is limited to power levels that do not force any stage of the receiver prior to the limiters into nonlinear operation.

On-Tune Non-FM Radar

The wind profiler receiver is susceptible to two forms of interference. The first interference mechanism affects the limiter diodes described in Section 2.5 and shown in the IF section of Figure 2-3. The limiters saturate at a receiver input power level of -106 and -101 dBm for the high and low mode, respectively, for signals in the IF pass band.

For the simple pulsed radar case, we assume a 1-μs pulse width (PW) and a pulse repetition frequency (PRF) of 300 Hz (PRT = 3.33 ms). The transmit spectrum of the radar has lines spaced at 300 Hz enveloped by a sinc function with a first-null bandwidth of ± 1 MHz. Since the interfering pulse has a nominal (3 dB) bandwidth of 1 MHz which is larger than the IF bandwidth of the profiler, the peak interference power levels at the receiver input required to activate the limiters are

$$-106 + 20\log\left(\frac{1\ MHz}{120\ kHz}\right) \approx -88\ dBm \tag{10}$$

for the high mode, and

$$-101 + 20\log\left(\frac{1\ MHz}{350\ kHz}\right) \approx -92\ dBm \tag{11}$$

for the low mode. If the interference power exceeds these levels, the wind profiler receiver will experience gain compression resulting in a decrease in the desired signal level. If the desired signal level is at a minimum level, the loss of signal due to gain compression could result in performance degradation of the wind profiler. The gain compression would occur for the time duration of the interfering signal plus any time associated with the recovery time of the limiter circuitry. However, the duty cycle of this event should be relatively small for typical radar signals representing operations in the 420-450 MHz band.

The second interference mechanism affects the detection process of the wind profiler receiver. When the interference adds noise to the receiver it affects the signal processing by reducing the signal-to-noise ratio in the detection circuitry. The interference power that is of concern to the detection process is limited (by the above mentioned limiters) to -88 dBm for the high mode and -92 dBm for the low mode. These peak power levels correspond to average powers of -123 and -127 dBm, respectively. If we assume that all of the average is confined to the 2-MHz first-null bandwidth and multiply this spectrum with the profiler frequency response (shown in Figures 3-3 and 3-4), we find that the total interfering power levels seen by the profiler are:

oblique high	-149 dBm
oblique low	-152 dBm
vertical high	-152 dBm
vertical low	-153 dBm.

Since these levels are about 10 dB below the system noise power for each mode, we would expect about 0.5 dB increase in noise and little significant interference to the profiler.

These results show that, for an interfering radar with the above assumed characteristics, interference power levels below -88 dBm for the high mode and -92 dBm for the low mode will have a minimum impact on the wind profiler detection process. At interference power levels above these values, the wind profiler receiver could experience gain compression effects. However, as explained later, the range-doppler processing capabilities of the wind profiler receiver should offer a considerable degree of immunity to low duty cycle interference such as that from radars operating in the 420-450 MHz band. Thus, the gain compression effects will probably not cause degradation until the threshold levels (-88 and -92 dBm) are exceeded by a considerable margin.

Off-Tune Non-FM Radar

As in the FM case above, the additional protection provided by the IF filters decreases the interference power by 45 and 80 dB for the low and high modes when the interfering radar is tuned 1 MHz off the profiler center frequency.

On-Tune Chirped Radar

We assume an interfering radar employs a 5-MHz chirped pulse width of 10 μs and a pulse repetition frequency of 300 Hz (PRT = 3.33 ms). The transmit spectrum could have a ± 2.5 MHz bandwidth. As in the case of non-FM radar above, the profiler receiver limiters could saturate and gain compression occur. The peak interference power levels that could result in initiation of limiting are -74 dBm for the high mode and -78 dBm for the low mode. At these levels, the average interference power levels in the noise filter would be

oblique high	-132 dBm
oblique low	-135 dBm
vertical high	-135 dBm
vertical low	-136 dBm.

These levels are 5 to 9 dB above the system noise levels for each mode, so we would expect the effect of the interfering radar to be detectable.

Off-Tune Chirped Radar

Since the interference of the co-channel radar described above is 5 to 9 dB above the system noise, we would expect that an adjacent channel chirped radar that is off-tuned sufficiently to realize 15 to 20 dB of frequency rejection due to the IF filters (see Figure 2-4) would not degrade the profiler detection process. That is, if the chirped bandwidth (± 2.5 MHz) is off-tuned by at least 500 kHz (i.e., a frequency difference of 3 MHz between the center frequency of the radar spectrum and the profiler tuned frequency), the radar signal would be sufficiently attenuated to protect the detection process. However, as above, peak power levels in an adjacent band large enough to saturate the limiters could cause interference.

Effect of Range-Doppler Processing

By considering the nature of interfering signals in the time domain, we discover that profilers enjoy a considerable degree of immunity from low duty cycle interference such as the radars described above. Since the profiler separates the returned signals in range and processes returns from thousands of pulses to obtain the Doppler information, it is unlikely that an interfering pulsed radar will maintain sufficient time or frequency coherence to interfere with a particular range-Doppler bin. For low duty cycle (e.g., < 1.0 %) pulsed interference, interfering signal levels of 50 dB above the receiver noise level can be suppressed due to range-Doppler processing.