SECTION 1
INTRODUCTION

1.1 BACKGROUND

Wind profiler radar systems provide hourly (or more frequent) wind speed and direction values as a function of altitude. The primary role for wind profilers is in weather observation and forecasting; however, other applications have been identified, including severe wind condition warnings, flight planning, space shuttle support, and pollution studies (acid rain and volcanic ash). Currently, wind speed and direction are determined by the National Weather Service (NWS)[a] and other agencies by tracking the flight path of radiosondes, which also provide information on temperature, barometric pressure, and relative humidity in the atmosphere along their flight paths. Radiosondes are expendable and are usually released twice daily. Although wind profilers are not direct replacements for radiosondes, they will provide regular, more frequent wind observations.

Wind profiler operations to date have been for experimental purposes at several research facilities. In addition, the National Oceanic and Atmospheric Administration (NOAA)[a] currently operates a demonstration network of 31 wind profilers and plans a national network of 100–200 units. Other Government [i.e., Department of Defense (DOD)] and non-Government wind profiler users are expected.

A concern about wind profiler operations is the selection of appropriate operating frequency bands. Atmospheric propagation characteristics require that wind profiler systems operate in the 50–1000 MHz range. Currently, three frequency ranges are of particular interest: around 50 MHz, 200–500 MHz, and around 900 MHz, each of which best accommodates a particular application. Since the NOAA plans a 200–500 MHz national wind profiler network, efforts to accommodate wind profilers have focused on that band.

No single frequency band is presently available to accommodate the 200–500 MHz type wind profiler operations for all users, Government and non-Government. Furthermore, the selection of any frequency band must take into account any potential international effect. For example, the wind profiler developed for NOAA at 404.37 MHz may be sold by its manufacturer to other countries, where conscientious attempts to protect operations such as COSPAS (COsmicheskaya Sistyema Poiska Avariynych-Russian Federation acronym for Space System for Search of Distressed Vessels) and SARSAT (Search And Rescue Satellite-Aided Tracking system) operating in the 406-406.1 MHz band may not be made. In addition, a frequency band selected solely on the basis of national usage may not be suitable for international usage, and thus national trade may be adversely affected. As a result, the Interdepartment Radio Advisory Committee (IRAC) requested that the National Telecommunications and Information Administration (NTIA)[a] conduct an assessment of the 216–225 MHz, 400.15–406 MHz, and 420–450 MHz bands to assist in determining the appropriate part of the spectrum for midfrequency (200–500 MHz) wind profiler radar operations.

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[a] Agencies within the United States Department of Commerce (DOC).

The requested study was completed by NTIA.[1] The study recommended that the 440–450 MHz band be considered for long-term wind profiler operations. It was noted that only limited wind profiler measurements had been conducted, and additional measurements would aid in verifying some of the assumptions made in the NTIA study. The test plan for these measurements was coordinated with NTIA's Institute for Telecommunication Sciences (ITS), NOAA, and various IRAC agencies.

The measurements were conducted on the Unisys wind profiler in Platteville, Colorado, operating on 404.37 MHz. It is assumed that the characteristics associated with the 404.37-MHz profiler would remain the same for profilers in the 200–500 MHz range, independent of any new frequency chosen.

1.2 OBJECTIVES

The objectives of the measurements on the Unisys wind profiler are as follows:

1. Determine the radiated short-pulse and long-pulse emission spectra of the wind profiler;
2. Determine the amplitudes of the wind profiler's radiated harmonics and subharmonics relative to the center frequency amplitude;
3. Determine any filter characteristics associated with the antenna;
4. Determine the gain of the profiler antenna at ground level relative to an isotropic antenna;
5. Determine the susceptibility of the profiler to various waveforms that represent typical systems operating in the 440–450 MHz band; and
6. Determine the effects of wind profiler emissions on a receiver that would represent typical land mobile/amateur operations.

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[1] Patrick, G. and Richmond, M. (1991), Assessment of Bands for Wind Profiler Accommodation (216–225, 400.15–406, and 420–450 MHz Bands), NTIA Report 91-280, September 1991.

1.3 APPROACH

To meet the above objectives, a preliminary measurement plan was developed and coordinated between NTIA/ITS, NOAA, and various IRAC agencies.[2] The plan was implemented in a series of measurements and tests on the profiler at Platteville, Colorado, in 1991.

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[2] NTIA/ITS, RSMS Measurement Plan on the Unisys wind profiler, May 1991.

SECTION 2
WIND PROFILER SYSTEMS

2.1 INTRODUCTION

The wind profiler is a vertically oriented, ground-based, pulsed Doppler radar that utilizes scattering from irregularities in the radio refractive index or precipitation to measure the horizontal and vertical components of wind velocity. A linearly polarized, phased-array antenna is sequentially steered in three directions, as shown in Figure 2-1. Data are collected from the three beams and processed at the profiler site. Every 6 minutes, data are sent via commercial satellite service to the Profiler Hub Computer in Boulder, Colorado, where it is processed further, and the resulting hourly averaged horizontal winds are sent to the NWS for distribution to forecast offices and used as input to numerical weather models. Data are also archived at the National Climatic Data Center in Asheville, North Carolina. In addition, a recent development, the Radio Acoustic Sounding System (RASS), which can be used in conjunction with a wind profiler allows the measurement of temperature profiles.

The data from profilers supplement data collected by the present upper-air balloon system and offer the following advantages:

1. Wind observations are available more than 10 times as often.
2. The wind profiles are obtained above the radar, as opposed to a downwind balloon track.
3. The radars run automatically and are unattended.

Given below is a description of the profiler's operation/function, system description, system hardware, and digital signal processing.

2.2 GENERAL OPERATION AND FUNCTION

The profiler described in this report is manufactured by Unisys Government Systems Group, Great Neck, New York. This profiler was designed to meet the requirements outlined in the Statement of Work for the DOC Request for Proposal NA-86-QA-C-1 01, August 1985. An analysis of the interference susceptibility and interfering potential of the wind profiler requires a detailed understanding of the operation and signal processing characteristics of the radar.

2.3 SYSTEM DESCRIPTION

Figure 2-2 shows a block diagram of the wind profiler radar. The radar operates on a 6-minute timing cycle consisting of three beam directions, each with two modes of 36 range gates. In normal operation the radar operates for about 1 minute each in the "east high," "east low," "north high," "north low," "vertical high," and "vertical low" modes. The selection of the north and east directions is arbitrary. In addition, there may be operational reasons (i.e., satellite passes) not to orient the antenna north and east beams in the true

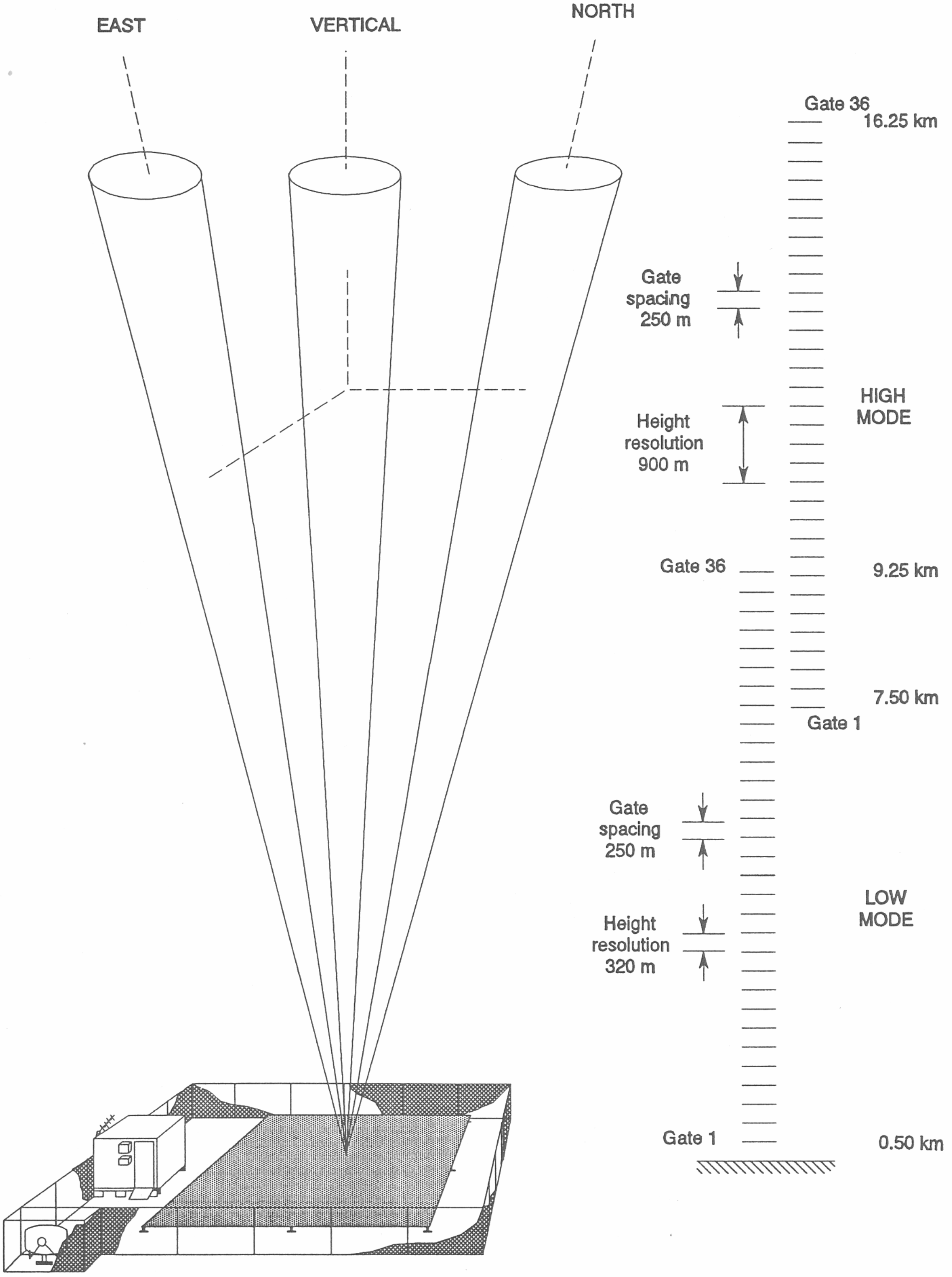

Figure 2-1. Wind profiler artist conception.

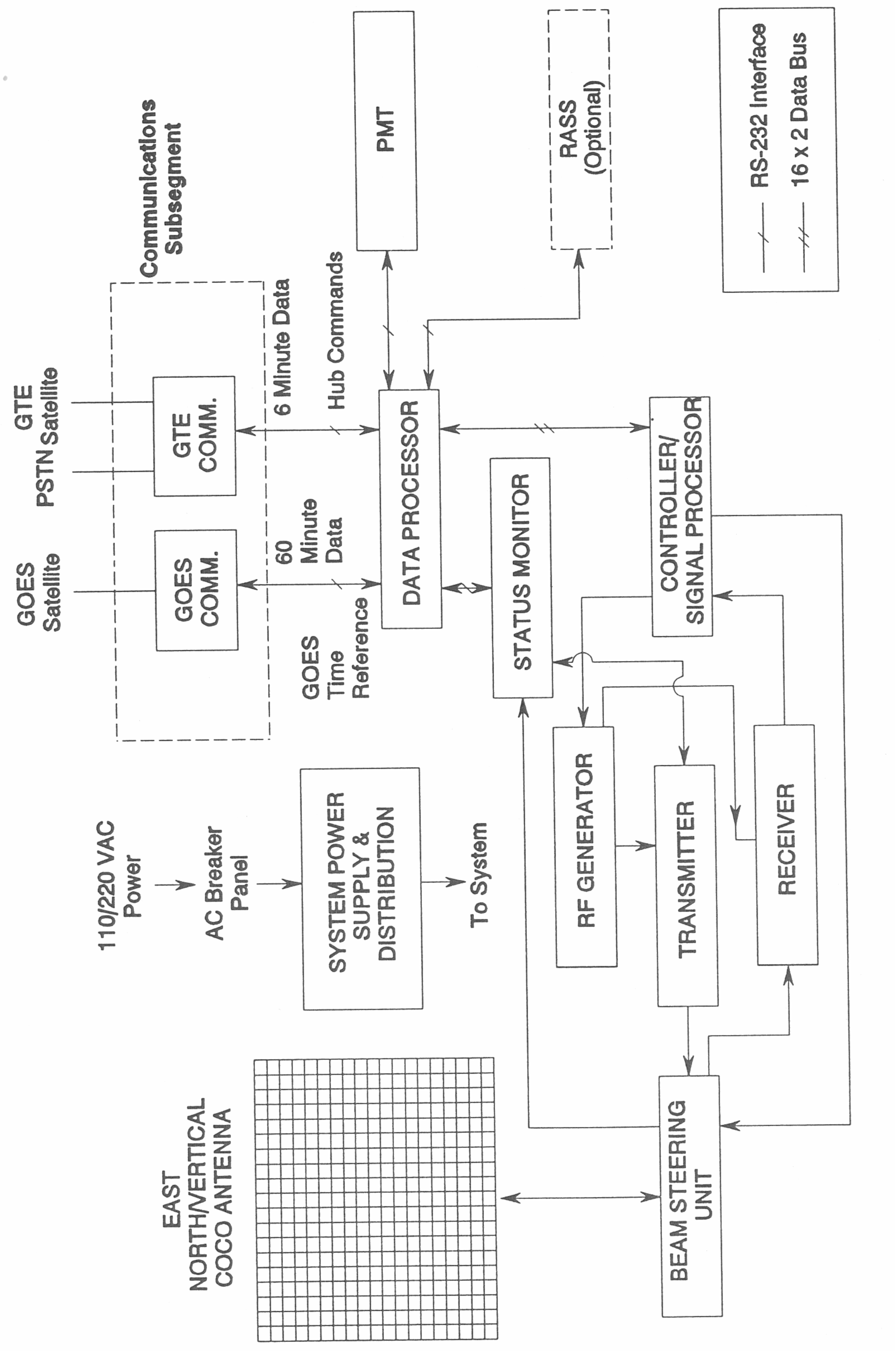

Figure 2-2. Wind profiler block diagram.

cardinal directions. At the end of this 6-minute cycle, the Doppler spectra for each of 216 (3 X 2 X 36) range gates have been reduced to three Doppler spectral moments and these "6-minute data" are sent to Boulder. As a backup, a reduced data set is transmitted over a Geostationary Operational Environmental Satellite (GOES) link once an hour. The system operation can be illustrated by following signals through the system from generation to processed output. Table 2-1 lists the profiler characteristics. The north and east beam timing are identical and referred to as oblique.

TABLE 2-1
PROFILER CHARACTERISTICS

	Low Mode		High Mode	
Operating frequency MHz	404.37		404.24	
Transmit power				
Peak (nom) kW	6.5		11.6	
Average (nom) W	215		1500	
Pulse width				
Coded *µs*	3.33		20.00	
Decoded *µs*	1.67		6.67	
Gate spacing m	250		250	
Range resolution m	320		900	
Lowest gate AGL m	500		7500	
Highest gate AGL m	9250		16250	
	Vertical	Oblique	Vertical	Oblique
Pulse repetition time *µs* *	96.667	100.694	148.333	154.514
Coherent averages (NTDA) *	152	118	100	52
Incoherent averages (NSA) *				
Submode A (summer)	30	39	30	57
Submode B (winter)	15	19	45	87
Max. ± Doppler freq. Hz *	34.03	42.08	33.71	62.23
Max. ± Doppler veloc. ms^{-1} *	12.62	15.61	12.50	23.08

* Discussed in Section 3.

2.4 SYSTEM TIMING WAVEFORMS

The controller/signal processor generates the system timing and the differential logic signals for the frequency generator to form the transmitter excitation. The timing is derived from a 14.4-MHz crystal oscillator, which is accurate and stable enough to meet the timing specifications. The four different operating modes are listed in Table 2-1.

Oblique High

In the oblique high mode, the signal processor generates a pulse of 20 *μ*s made up of three 6.67-*μ*s "chips," resulting in a pulse compression ratio of 3:1. The complementary code set

A = + + +
B = + - +
C = + + - ,

where + indicates a 0° phase shift and - indicates a 180° phase shift, is transmitted in the sequence C, A, C, B, C, A, C, B,... with a pulse repetition time (PRT) of 154.514 *μ*s. Beginning at a height 017.5 km, 36 samples are taken 1.7361 *μ*s apart, which, considering the 73.7° beam elevation angle, corresponds to a vertical spacing of 249.95 m. The last sample is taken at 16.25 km above ground level (AGL).

Oblique Low

The oblique low mode uses a pulse duration of 3.33-*μ*s consisting of two 1.67-*μ*s chips, for a pulse compression of 2:1. The complementary code set

A = + +
B = + -

is transmitted in the sequence A, B, A, B, A, B,... with a PRT of 100.694 *μ*s. The 36 samples are taken as above, at 1.7361-*μ*s (249.95-m) intervals from 0.5 to 9.25 km AGL.

Vertical High

The vertical high mode uses the same pulse duration and pulse coding as the oblique high mode. The PRT is 143.333 *μ*s and the 36 samples are taken at 1.667-*μ*s intervals, which, with the vertical beam orientation, corresponds to 250-m spacing from 7.5 to 16.25 km AGL.

Vertical Low

The vertical low mode uses the same pulse duration and pulse coding as the oblique low mode. The PRT is 96.667 *μ*s and the 36 samples are spaced 250-m from 0.5 to 9.25 km AGL.

Additional timing requirements of the controller/signal processor are discussed in Section 2.6 on signal processing.

2.5 PROFILER SYSTEM HARDWARE

Frequency Generator

The frequency generator contains two independent, low-noise, temperature-controlled, crystal oscillators. The local oscillator (LO) at 374.22 MHz ± 0.005% and the coherent oscillator (COHO) at 30 MHz ± 0.005% are mixed and pulse modulated to form the transmitter excitation at +12 dBm. In addition to the phase coded pulses, successive radar pulses are pseudorandomly phase shifted using a sequence of length 64, so the separation between spectral lines is PRF/64, not PRF. This additional encoding is used to reduce range-ambiguous returns. To accomplish this function, the LO is phase shifted from pulse to pulse by a 3-bit phase shifter under control of the signal processor. The COHO is biphase modulated with the pulse code, then filtered by a 30.3-MHz surface acoustic wave (SAW) device that performs a minimum-shift keying (MSK) modulation which reduces the transmitted spectrum sidelobe levels at the expense of range resolution. As a result of the MSK pulse coding, the high-mode radiated spectrum is asymmetric with its peak at 404.24 MHz and the low-mode spectrum is symmetric with its center at 404.37 MHz.

The pulse-to-pulse, phase-shifted LO and unmodulated COHO signals, at a level of +15 dBm, are also sent to the receiver, providing the coherence between transmitted and received signals.

RF Power Amplifier

The radio frequency (RF) power amplifier accepts the low-level (10 mW) signal from the frequency generator and amplifies it for transmission. It consists of a redundant driver amplifier, which amplifies the signal to about 80 W, and a solid-state power amplifier consisting of 16 modules operating in parallel, each of which is capable of 1.2 kW peak output. Table 2-2 lists the power amplifier characteristics. The amplifier is typically run at an average power level of 1.5 kW average (11.6 kW peak) in the high modes and about 215 W average (6.5 kW peak) in the low modes.

Antenna

The profiler employs a coaxial-collinear (COCO) antenna for both transmission and reception. The antenna characteristics are listed in Table 2-3. Individual COCO elements are constructed from low-loss coaxial cable whose inner and outer conductors are exchanged every one-half wavelength inside the cable. The radiation characteristic of the COCO element is similar to feeding an equivalent number of collinear dipoles with equal amplitude and phase. The advantage is that the COCO elements require only one feed point as opposed to feeding the individual dipoles. One disadvantage is that each "dipole" in the row cannot be phased individually. This limitation is overcome by employing two orthogonal arrays with individual rows of elements that are phased to generate a beam broadside to the element axis. The profiler uses one array for the north and vertical beams, and the superimposed, orthogonal array for the east beam. The COCO elements are positioned about one-quarter wavelength above a metal mesh ground plane, and the resulting square arrays have a physical aperture of 100 m^2. For reliability reasons, all the beam steering switches are inside the equipment shelter.

TABLE 2-2
RF POWER AMPLIFIER CHARACTERISTICS

Max. RF output power	16 kW peak 2.2 kW average
RF input power	10 mW peak (nominal) ± 2 dB adjustment range
Bandwidth -1 dB	6 MHz
Bandpass flatness	± 0.5 dB (maximum)
Interpulse spurious noise	< -1 00 dBm/MHz
Interpulse phase stability	<10°
Intrapulse phase stability	<10°
Operating VSWR	2.0:1 all phase angles
Cooling	forced air
Input prime power	230/115 Vac ± 15% 3-wire single-phase

TABLE 2-3
PROFILER ANTENNA CHARACTERISTICS

Frequency	404.37 ± 0.5 MHz
One-way -3 dB beamwidth (all beams)	≤ 5°
One-way peak sidelobe levels (all beams, relative to on-axis peak level)	
For elevation angle ≥ 45°	< -20 dB
For 5° < elevation angle < 45°	< -25 dB
For elevation angle ≤ 5°	< -40 dB
On-axis gain (above isotropic)	≥ 32 dBi
Number of beams (sequentially scanned)	3
Oblique beam elevation angle	73.7°
Vertical beam elevation angle	90.0°
Maximum beam pointing error from nominal	
Elevation	± 0.5°
Azimuth	± 2.0°
Input VSWR	< 1.2:1

Receiver

The backscattered signals are routed from the antenna to the receiver through a circulator, a limiter, and a solid-state transmit/receive (T/R) switch. The receiver is described in detail because the interference analysis depends on the receiver characteristics listed in Table 2-4. Figure 2-3 shows that the receiver is a single-conversion, superheterodyne design comprised of RF, intermediate-frequency (IF), and analog-to-digital (A/D) assemblies.

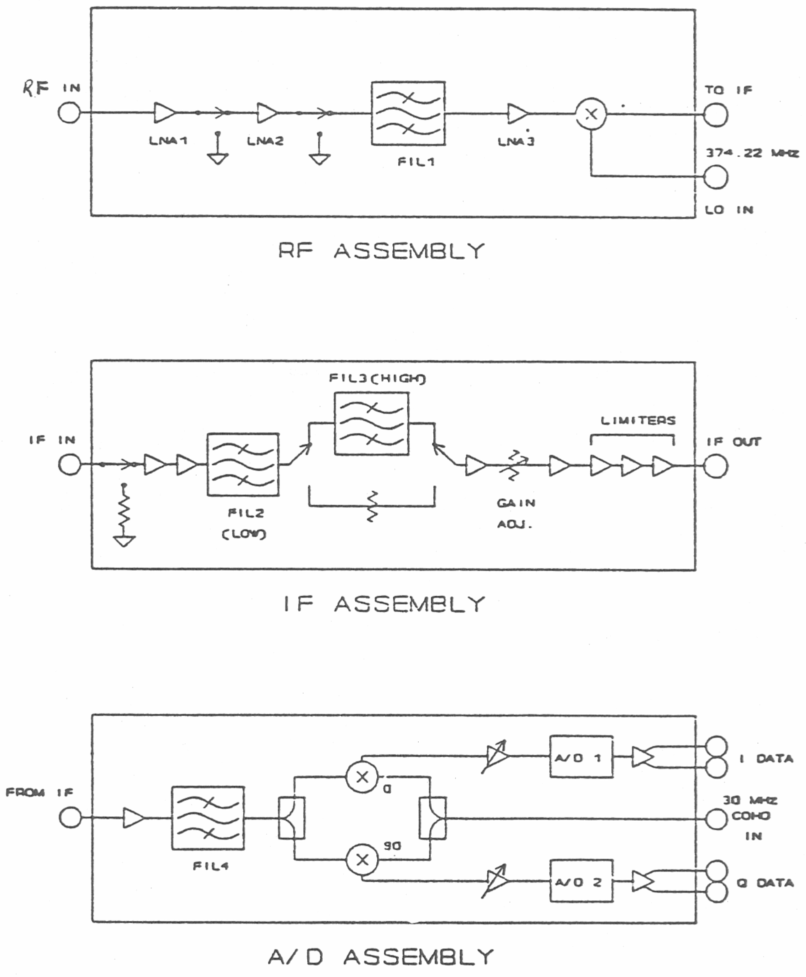

Figure 2-3. Profiler receiver block diagram.

TABLE 2-4
RECEIVER CHARACTERISTICS

Noise figure (dB)	0.53	
Spectral image rejection (dB)	30	
T/R recovery time (ns)	200	
	Low Mode	High Mode
Rf signal center frequency (MHz)	404.37	404.24
Full-scale RF input level (dBm)	-101	-106
IF bandwidth		
-3 dB bandwidth (kHz)	350	120
-10 dB bandwidth (kHz)	600	200

Receiver RF Assembly

Low-noise (0.5 dB) GaAs Field Effect Transistor (FET) amplifiers are used at the input to minimize the receiver noise figure. Two P-intrinsic-N (PIN) diode reflective switches attenuate the signal during transmission to limit receiver saturation. A preselection filter is positioned before the high-level (+ 17 dBm) mixer. The gain and noise figures of the RF assembly are 38 dB and 0.53 dB, respectively.

Receiver IF Assembly

An absorptive PIN diode switch is followed by two amplifiers and the low-mode bandpass filter, FIL2, which has a nominal -3 dB bandwidth of 350 kHz, centered at 30.15 MHz. Two switches select either an attenuator in the low-mode filter, or the high-mode filter, FIL3, which has a nominal -3 dB bandwidth of 120 kHz, centered at 30.02 MHz. Fourth-order Bessel filters matched to the -3 dB and -10 dB levels of the transmit spectrum are used because of their linear phase response. The filter magnitude responses are shown in Figure 2-4. The filters are followed by amplifiers, gain adjustment, and three low-phase-shift limiters. The gain of the IF assembly is 64.5 dB.

Receiver A/D Assembly

The function of the A/D assembly is to convert the 30-MHz IF signal into digital in-phase and quadrature (I & Q) samples. It consists of an input amplifier, wideband noise filter, and an in-phase splitter that applies the IF signal to mixers MXR2 and MXR3 which are fed by in-phase and quadrature versions of the 30-MHz COHO. The resulting I & Q video signals are converted to 8-bit, two's complement integers by two A/D converters under the control of the controller/signal processor. The amplitudes and phases of the two channels in the quadrature detector are balanced to ensure an image rejection of at least 30 dB in the Doppler spectrum.

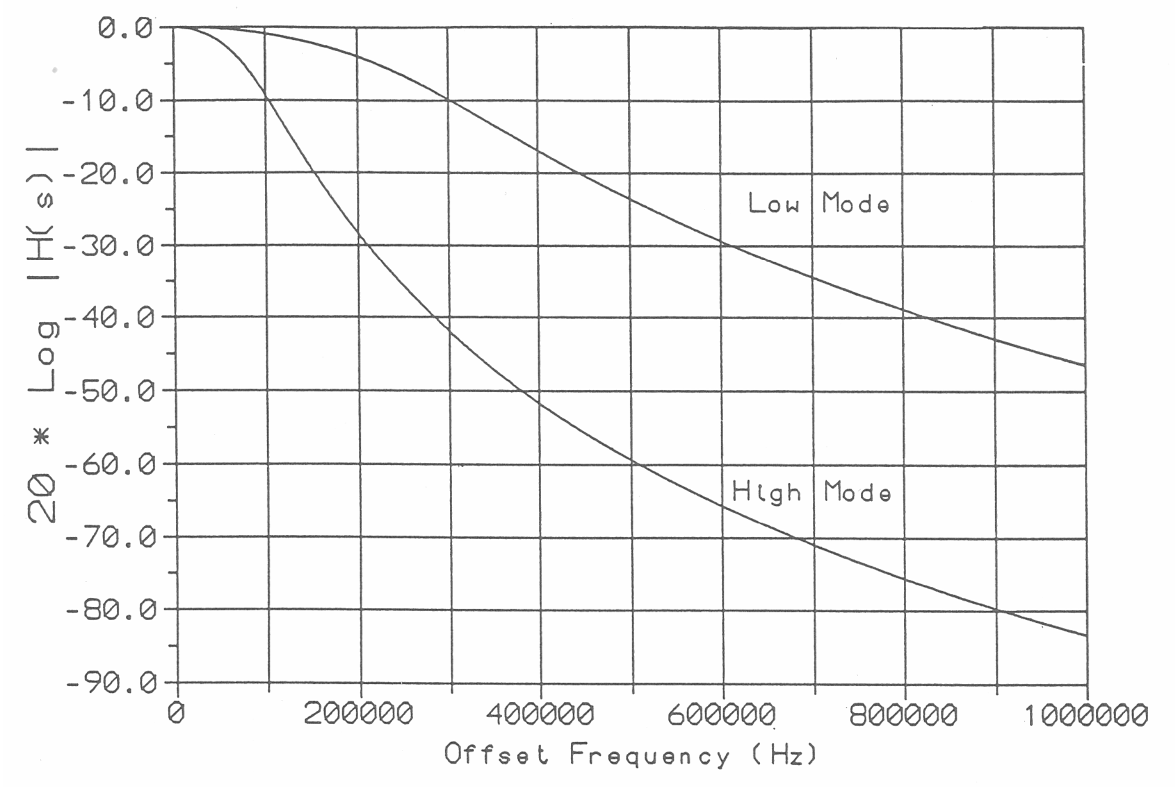

Figure 2-4. Frequency response of IF filters.

2.6 DIGITAL SIGNAL PROCESSING (PROFILER)

The 8-bit I & Q values from the A/D converters are decoded to recover the full range resolution, then coherently (phase-preserving) summed, sometimes referred to as time domain averaging (TDA). The final step of the averaging process, division by the number of sums, is performed on the fast Fourier transform (FFT) processor. Table 2-1 lists the number of coherent averages for each beam and mode. The coherent averaging reduces the data rate as well as the noise bandwidth by the number of time domain averages (NTDA), and the resulting frequency response of the averager is a narrowband comb filter. The filter response is described in detail in Section 3.5.

The summed signals are sent to the FFT processor in the main computer. The FFT processor performs the following processing steps: the final step of the averaging process (division by NTDA), accumulation of 128-point time series, DC removal, complex FFT, and Hanning window. All the processing to this point is coherent; that is, it preserves the phase (Doppler) information in the signal. The complex spectral data are sent to the main computer, which calculates the 128-point power spectrum and averages a number (NSA in Table 2-1) of these spectra. This second averaging process is incoherent since the phase information is lost in the calculation of the power spectrum. The signal-to-noise ratio (SIN) increases linearly with coherent averaging time or the coherence time of the signal, whichever is less, and the signal detectability is improved by an amount equal to the square root of the number of incoherent averages.

The total dwell time (in seconds) in any beam mode is

$$t_{dwell} = (PRT)(NTDA)(NFFT)(NSA)\,, \qquad \textbf{(1)}$$

where

t_{dwell} = the dwell time (s)
NFFT = the number of FFT points (128)
NSA = the number of (incoherent) spectral averages.

Using the values from Table 2-1, it is seen that the nominal dwell time for each beam in submode A is close to 1 minute. In submode B, the winter mode, the profiler spends more time in the high modes than in the low modes. This submode B is not currently in operational use.

The data processor removes ground clutter by replacing frequency components close to zero Doppler with values interpolated from neighboring points. At this point, the received spectra are ready for moment estimation, which consists of four main steps. The first step is to calculate the mean noise level using an objective algorithm.[3] Once the noise level is determined, the algorithm scans for the peak in the spectrum using a five-point running average. This average is used to distinguish narrow noise peaks from the (presumably) wider atmospheric return. Once the peak is determined, the atmospheric signal is defined as that part of the original (unsmoothed) spectrum from the peak down to the noise level. Then the zeroth moment, representing the signal power; the first moment, representing the mean Doppler velocity; and the second moment, representing the velocity variance, are calculated. Figure 2-5 shows an actual Doppler spectrum with the noise level, the zeroth, first, and second spectral moments indicated. The three spectral moments for each beam, mode, and range gate are the raw data that are sent to Boulder every 6 minutes. The normal data message is approximately 3000 bytes.

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[3] Hildebrand, P.H. and Sekhon, R.S., Objective Determination of the Noise Level in Doppler Spectra, Journal of Applied Meteorology, *No. 13,* October 1974.

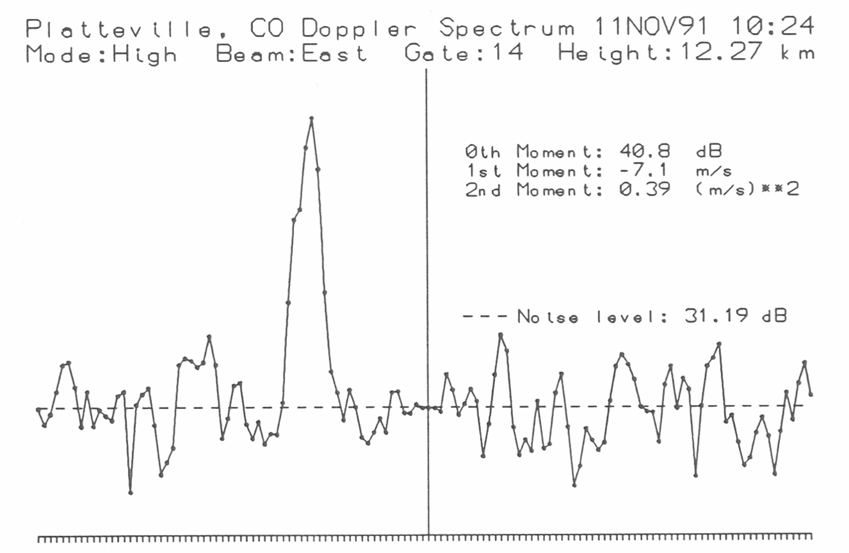

Figure 2-5. Profiler doppler spectrum.

Profiler Hub Processing

The Profiler hub computer system accepts data from the profiler network, generates the wind products, and monitors the health of the individual profilers by analyzing the status information sent along with the spectral moment data every 6 minutes.

Consensus Averaging

Every hour the hub performs a consensus average on the ten 6-minute velocity samples for each beam, mode, and gate. The consensus algorithm requires that the samples agree with one another to within a velocity range (typically one-sixteenth the Nyquist interval) in order to be averaged together. The number of samples that fall within the consensus window is called the consensus value, which can be used as an indicator of data consistency. If the consensus value is less than four, that is, less than four samples fall within the consensus velocity window, then there is no radial velocity estimate for that beam, mode, and gate. The consensus method has been found to be a simple and robust averaging method that helps prevent erratic velocities, such as returns from aircraft, from biasing the estimate of the hourly averaged radial velocity.

Wind Calculation

For each of the 36 heights in the low and high modes, the horizontal wind is calculated from the consensus-averaged radial velocities from the three beams. If the radial velocity from any of the three beams is missing due to lack of consensus, the horizontal wind is not calculated. Missing winds are not interpolated or extrapolated. As an indicator of the quality of this wind calculation, one may ask, “What is the probability of a wind estimate in the absence of any signal?" Assuming uniformly distributed random velocities (as is the case for no systematic biases), the consensus average will generate a radial velocity with a probability of 0.0676 (6.76%). Since velocity estimates are required for all three beams, the probability of an erroneous wind estimate is 0.0003, or (0.03%).

In practice, one needs to be more concerned with systematic sources of error, such as low-level signals emitted from the radar itself that are coupled in through the antenna, or ground clutter signals that are too wide or too strong to be handled by the clutter removal processing.

Once the radial velocities from the three beams are estimated, the three-dimensional wind velocity is

$$u' = \frac{-V_\theta}{\cos\Theta_n} + V_z \tan\Theta_\theta$$

$$v' = \frac{-V_n}{\cos\Theta_n} + V_z \tan\Theta_n \tag{2}$$

$$w' = -V_z,$$

where *u', v',* and *w'* are the east, north, and vertical wind components (positive = away) referenced to the east and north beam directions, and V_θ, V_n, and V_z are the measured Doppler velocities (positive = towards the radar) on the east, north, and vertical beams. Θ_θ and Θ_n are the elevation angles of the east and north beams, respectively. The vertical beam has an elevation angle of 90°.

If the antenna array is oriented Φ° clockwise from true north, then the u (east), v (north), and w (vertical) wind components are

$$\begin{aligned} u &= u'\cos\Phi + v'\sin\Phi \\ v &= -u'\sin\Phi + v'\cos\Phi \\ w &= w'\,. \end{aligned} \qquad \textbf{(3)}$$

The last line of defense is processing that exploits the consistency of the atmosphere in height and time to filter out erroneous wind estimates. The end result is that the wind velocity data delivered from the hub computer are either very good or missing.