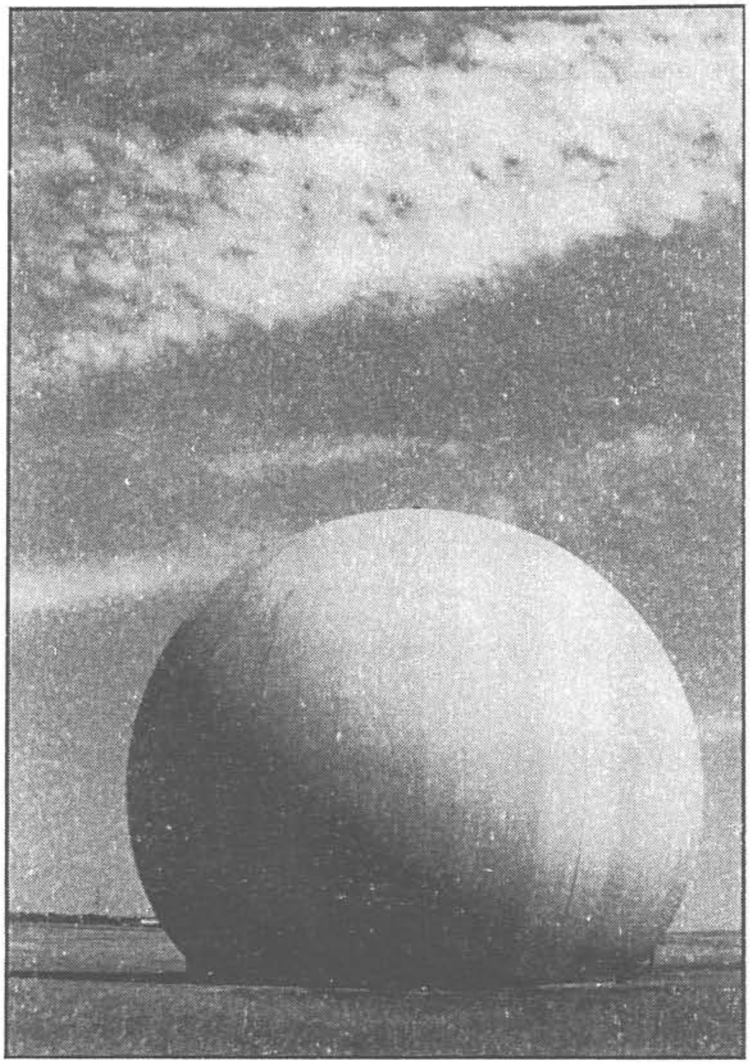
CHILL RADAR
DATA ANALYSIS GUIDE



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CHILL RADAR
DATA ANALYSIS GUIDE

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1. Introduction

It is likely that an almost infinite variety of methods exist for analyzing radar data; so the compilation of a single "analysis guide" is somewhat presumptuous. However, most of these analysis procedures are sensitive to the intrinsic characteristics of the measurement and the manner in which the basic radar data is collected. Inappropriate data collection procedures can render certain data analysis methods useless. Furthermore, variations in the implementation of these procedures can strongly affect the quantity of magnetic tape required for data storage and archiving.

The purpose of this manual is to present a general overview of the data collection parameters for the CHILL radar (designed and developed jointly by the University of CHicago and the ILLinois State Water Survey) that may impact on data analysis and storage. Careful consideration of these parameters during the design of data collection procedures can aid both the subsequent analysis and the efficient usage of tape.

2. Limits on Areal Coverage

Several factors impose physical limits on the atmospheric volume in which radar data may be collected. Clearly, no data can be obtained from regions that cannot be illuminated by the transmitted pulse. Also, hardware limitations may prevent the processing of some of the signal that is backscattered to the radar.

2.1. Height Constraints

The lowest height that the radar can observe is limited by the propagation path of the transmitter beam. When the atmospheric refractive index profile is "normal" (i.e., fairly well-mixed conditions), the radar beam height is given by:

$$H = \text{sqrt}\,[R*R + A_e*A_e + 2*R*A_e*\sin(\text{theta})] - A_e \qquad (1)$$

where

A_e = effective earth radius (4/3 of the earth's radius)

H = beam height above ground level (AGL) in the same units as A_e

R = slant range in the same units as A_e

theta = antenna elevation angle

A simple approximation for this relationship is:

H = 1/2*R*R + 5280*R*sin(theta)

where

H = beam height in feet AGL

R = slant range in statute miles

The use of a zero degree elevation angle gives the lowest beam heights. However, at this elevation angle, the lower half of the main beam radiation pattern strikes the ground. If the ground fully absorbs this radiation, there are 3 decibels (dB) less transmitted power available for echo illumination. The ground may also reflect a variable portion of the incident radiation back upward. To reduce these effects, a minimum elevation angle of 0.5 degrees is often used. The proper determination of the lowest usable elevation angle is dependent on the obstruction characteristics at a given radar site.

2.2. Range Constraints

The maximum unambiguous range that the radar can observe is a function of the transmitter pulse repetition time (PRT) and is given by:

$$R_{max} = (C*PRT)/2 \qquad (2)$$

where

R_{max} = maximum range

C = speed of light

PRT = pulse repetition time

A longer PRT reduces the occurrence of range ambiguity (second trip echo). Unfortunately, a long PRT increases the likelihood of velocity ambiguity (folding). The maximum unambiguous velocity is given by:

$$V_n = lambda / (4*PRT) \qquad (3)$$

where

V_n = magnitude of the maximum unambiguous velocity (Nyquist velocity)

lambda = radar wavelength

PRT = pulse repetition time

The CHILL routinely uses a PRT of 1040 microseconds, which yields a maximum unambiguous range of 156 kilometers (km) and a Nyquist velocity of 26.42 meters per second (m/s). In general, the tradeoff involved in making unambiguous range and velocity measurements with a single PRT is shown by:

$$R_{max}*V_n = (C*\text{lambda}) / 8 \qquad (4)$$

where the symbols retain their earlier definitions.

In the CHILL system, this tradeoff can be improved by periodic alternation between two different PRTs. During such staggered PRT operations, range and returned power measurements are based on the longer PRT series, and velocity calculations are based on the shorter PRT data.

Many of the residual range and velocity ambiguities can be corrected in post-processing of the recorded data. However, these editing procedures are often tedious and time-consuming, making it worthwhile to avoid them in real time. The CHILL system allows the user to select PRTs between 800 and 4080 microseconds in 16-microsecond steps. In some cases, a judicious choice of PRT can reduce both range and velocity ambiguities.

The minimum range at which radar measurements can be made is set by switching constraints in the transmitter signal path. When differential reflectivity measurements are being made, the required cycling of the polarization switch prevents the observation of any targets within a range of 2.1 km. The polarization switch can be bypassed if single polarization data is sufficient. This reduces the minimum range to 300 meters.

3. Spatial Resolution in the Recorded Data

Several user-selectable parameters control the data resolution within the radar observation volume. Factors affecting the range and azimuth resolution in the recorded data will be considered separately.

3.1. Range Resolution

Range resolution is determined by the duration of the transmitter pulse. The pulse lengths available in the CHILL system give range resolutions of 37.5, 75, and 150 meters. Operation at less than the customary 150-meter range resolution imposes two penalties: (1) hardware and data rate limitations may prevent processing all the data out to long range when short gate lengths are used; and (2) the gate length directly affects the strength of the returned power level. Halving the gate length reduces the strength of the returned power by 50%. In addition, since the bandwidth must be increased by 2 to accommodate the shorter pulse length, the noise power increases by a factor of 2. Thus the minimum detectable signal level is increased by a factor of 4 (net loss from both effects of 6 dB). As a result, the capability to detect weak echoes is reduced during short-gate-length operations.

3.2. Azimuth Integration Angle and Azimuth Resolution

The azimuth resolution as usually defined is a combination of the frequency of reporting, the antenna beam width, and the data integration algorithm that is in use. Strictly speaking, the antenna resolution refers to the ability of the system to separate two point targets separated in azimuth. Often the azimuth reporting angle is referred to as the azimuth resolution. In the case of the CHILL system, the azimuth integration angle is defined as the angle traversed by the antenna during one integration or computational cycle. In some systems the reporting angle can be different from the integration interval, thus allowing either oversampling or undersampling of the variable. In the CHILL system, the only procedure that can be invoked is to decrease the integration time to allow the oversampling in the beam width.

The azimuth integration interval in the data is given by:

$$\text{azint} = \text{azrate}*\text{HITS}*\text{PRT} \qquad (5)$$

where

azint = azimuth integration interval in the recorded data

azrate = antenna rotation rate

HITS = number of transmitter pulses integrated into each sample

PRT = pulse repetition time

As discussed earlier, the PRT value in this equation is usually determined by requirements on unambiguous range and velocity measurements. Assuming that PRT is fixed, the usual practice is to select a HITS value that allows an adequate number of independent echo samples to be taken. This HITS value, in combination with the desired azimuth resolution in the data, defines the antenna azimuth rotation rate. The factors involved in choosing an appropriate number of PRTs for several types of measurements are examined in the next section.

4. Time to Independence for CHILL Operation Characteristics

The accuracy of the estimate of radar variables commonly used in meteorology depends on the number of independent samples that go into the calculation of the variable. Compromises usually must be made in designing a scanning procedure. The slower the antenna moves, the longer the time available for sampling and thus, for a given azimuthal resolution, the smaller the sampling error. On the other hand, it takes longer to observe the total storm when the antenna is moving slowly. Thus compromise is necessary between duration of observation, accuracy of estimate, and resolution of the measurements. This section has been prepared in an attempt to clarify these issues and to at least give some quantification to the sort of compromises among these parameters.

The assumptions made in the following discussion, tables, and figures are as follows:

1. The echoing volume is homogeneous in the sense that the true parent populations of the scatterers generating the reflectivity remain constant in both time and space for a sampling period.

2. The receiver is assumed to be of the "square law" type. That is, the power returned is averaged rather than either the logarithm of the power or the magnitude of the absolute voltage. This is true for the CHILL system for reflectivity.

3. The antenna beam pattern is represented by a Gaussian distribution. This is the assumption made by Probert-Jones in the 1960s in deriving the radar equation that is in general use today. It is a good approximation of the actual pattern and is tractable to computation.

4. The PRT is 1.040 milliseconds. This is the nominal value in use for the CHILL system, although there is complete flexibility to change this between 800 microseconds and several milliseconds.

5. The one-half power beam width of the CHILL system is one degree.

6. The spectral shape of the frequency distribution of the weather echo is also assumed to be Gaussian. This assumption is also inherent in the method chosen to estimate both mean velocity and spectral width (i.e., the standard autocorrelation algorithm).

4.1. Reflectivity

Reflectivity is one of the most important of the variables that are routinely calculated. The source of the equations used to estimate the effective number of independent samples in a group is a paper by Walker et al. (1980). The accuracy of the estimate given the number of independent samples is obtained from Marshall and Hitschfeld (1951).

One of the variables that affects the accuracy of the estimate of reflectivity is the spectral width of the velocity distribution of the weather target. The spectral widths of common weather targets vary from about 1 meter per second (m/s) in snow to greater than 15 m/s in tornado conditions. Tabulations of the number of equivalent independent samples as a function of this spectral width are calculated for widths from 1 m/s to 8 m/s.

In the CHILL system, an output estimate will occur for each integration interval, referred to as a sampling period. The actual angular space contributing to this estimate is greater by the beam width, so that in reality there is a small amount of oversampling in azimuth if the azimuth integration angle is set to equal the half-power beam width, which is the conventional setting. This oversampling is inherent in any system in which all of the PRTs are used in a calculation. Because of this, the number of independent samples increases by a factor of more than one when the antenna moves only one beam width. This is reflected in table 1 by the column labeled "Eff" (for effective width), which shows the apparent increase in the spectral width due to the antenna speed.

Tables la through lg present the number of effective independent samples for different meteorological spectral widths and for antenna speeds from 0 to 30 degrees per second (deg/s). These tables refer to measurements of the reflectivity alone. Figure 1, which is taken from Marshall and Hitschfeld (1951), with the vertical scale changed to decibels, reflects the distribution of estimates of the average power as a function of the effective number of independent samples in the estimate.

Table 2 is an alternate procedure for determining the number of independent samples required to obtain a particular accuracy. In this table, the standard deviation of the estimate of the non-logarithmic reflectivity is converted to logarithms (dB scale). This conversion does not reflect the true standard deviation of the distribution of the logarithmic reflectivity. This effect can be seen in figure 1 by noting that the dB scale on the right ordinate shows considerably different values at the points of 25% and 75% curves.

As an example of usage of tables 1 and 2, suppose that it is desired to have a standard error of estimate for reflectivity of 0.5 dB and a desired azimuth integration angle of <= 1 deg. This standard error of estimate requires 67 independent samples (table 2). One notes that at antenna speeds of 30 deg/s, even for the widest of meteorological spectrum widths considered and with a 4.4-degree azimuth integration angle, only 56 independent samples could be obtained. Actually, for most cases the meteorological width will be nearer to 4 m/s, and thus this would be a more appropriate value to use in the table. At antenna speeds as slow as 5 deg/s and at a width of 4 m/s, there are only 39 independent samples, even at 180 hit integration. Thus this sort of accuracy (0.5 dB standard error) is difficult to obtain in any fast scanning procedure unless there is recourse to range averaging or different means of obtaining independence. If the requirement is relaxed to 1 dB standard error, then only 15 samples are required. This can be accomplished at an antenna speed of 15 deg/s with about 70 PRTs and with the desired azimuth integration angle.

Table 1. Number of Effective Independent Samples for Estimation of Reflectivity as a Function of Antenna Speed and Meteorological Spectral Width for CHILL Parameters and PRT=1.04 milliseconds

Table 1a. Antenna Speed = 0 deg/s

*Width, m/s**		*Hits*						
		60	80	100	120	140	160	180
Met	*Eff*	*Number of effective independent samples*						
1	1.00	4.2	5.3	6.4	7.5	8.7	9.8	10.9
2	2.00	7.3	9.5	11.7	13.9	16.1	18.4	20.6
3	3.00	10.3	13.5	16.8	20.0	23.3	26.5	29.7
4	4.00	13.2	17.4	21.6	25.8	30.0	34.2	38.4
5	5.00	15.9	21.0	26.1	31.3	36.4	41.5	46.6
6	6.00	18.5	24.5	30.5	36.5	42.5	48.5	54.5
7	7.00	20.9	27.8	34.6	41.4	48.2	55.1	61.9
8	8.00	23.3	30.9	38.5	46.1	53.8	61.4	69.0
Azimuth angle		0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table lb. Antenna Speed = 5 deg/s

*Width, m/s**		*Hits*						
		60	80	100	120	140	160	180
Met	*Eff*	*Number of effective independent samples*						
1	1.10	4.5	5.7	7.0	8.2	9.5	10.7	12.0
2	2.05	7.5	9.7	12.0	14.3	16.5	18.8	21.1
3	3.04	10.4	13.7	17.0	20.2	23.5	26.8	30.1
4	4.03	13.2	17.5	21.7	25.9	30.2	34.4	38.6
5	5.02	15.9	21.1	26.2	31.4	36.5	41.7	46.8
6	6.02	18.5	24.5	30.5	36.6	42.6	48.6	54.6
7	7.02	21.0	27.8	34.6	41.5	48.3	55.2	62.0
8	8.01	23.3	30.9	38.6	46.2	53.8	61.5	69.1
Azimuth angle		0.31	0.42	0.52	0.62	0.73	0.83	0.94

*Met = meteorological spectral width; Eff = effective spectral width, a result of antenna motion

Table 1c. Antenna Speed = 10 deg/s

*Width, m/s**		*Hits*						
		20	40	60	80	100	120	140
Met	*Eff*	*Number of effective independent samples*						
1	1.37	2.5	3.8	5.3	6.8	8.4	9.9	11.5
2	2.21	3.2	5.5	7.9	10.4	12.8	15.2	17.7
3	3.14	4.0	7.3	10.7	14.1	17.5	20.9	24.2
4	4.11	4.9	9.2	13.5	17.8	22.1	26.4	30.7
5	5.09	5.7	10.9	16.1	21.3	26.5	31.7	36.9
6	6.07	6.5	12.6	18.7	24.7	30.8	36.8	42.9
7	7.06	7.3	14.2	21.1	28.0	34.8	41.7	48.6
8	8.05	8.1	15.7	23.4	31.1	38.7	46.4	54.0
Azimuth angle		0.21	0.42	0.62	0.83	1.04	1.25	1.46

Table 1d. Antenna Speed = 15 deg/s

*Width, m/s**		*Hits*						
		20	40	60	80	100	120	140
Met	*Eff*	*Number of effective independent samples*						
1	1.72	2.7	4.5	6.4	8.3	10.3	12.2	14.1
2	2.44	3.4	6.0	8.6	11.3	14.0	16.7	19.4
3	3.31	4.2	7.7	11.2	14.8	18.3	21.9	25.4
4	4.24	5.0	9.4	13.8	18.3	22.7	27.1	31.6
5	5.19	5.8	11.1	16.4	21.7	27.0	32.3	37.6
6	6.16	6.6	12.7	18.9	25.0	31.1	37.3	43.4
7	7.14	7.4	14.3	21.3	28.2	35.1	42.1	49.0
8	8.12	8.1	15.8	23.6	31.3	39.0	46.7	54.4
Azimuth angle		0.31	0.62	0.94	1.25	1.56	1.87	2.18

Table 1e. Antenna Speed = 20 deg/s

*Width, m/s**		*Hits*						
		20	40	60	80	100	120	140
Met	*Eff*	*Number of effective independent samples*						
1	2.12	3.1	5.3	7.7	10.0	12.4	14.7	17.1
2	2.74	3.6	6.6	9.5	12.5	15.5	18.5	21.4
3	3.54	4.4	8.1	11.9	15.6	19.4	23.2	26.9
4	4.42	5.2	9.7	14.3	18.9	23.5	28.1	32.7
5	5.34	5.9	11.4	16.8	22.2	27.6	33.1	38.5
6	6.29	6.7	12.9	19.2	25.4	31.7	37.9	44.1
7	7.25	7.5	14.5	21.5	28.5	35.6	42.6	49.6
8	8.22	8.2	16.0	23.8	31.6	39.3	47.1	54.9
Azimuth angle		0.42	0.83	1.25	1.66	2.08	2.50	2.91

Table 1f. Antenna Speed = 25 deg/s

*Width, m/s**		*Hits*						
		20	40	60	80	100	120	140
Met	*Eff*	*Number of effective independent samples*						
1	2.55	3.5	6.2	9.0	11.7	14.5	17.3	20.1
2	3.08	4.0	7.2	10.5	13.8	17.2	20.5	23.8
3	3.81	4.6	8.6	12.6	16.6	20.7	24.7	28.7
4	4.64	5.3	10.1	14.9	19.7	24.5	29.3	34.1
5	5.52	6.1	11.7	17.2	22.8	28.4	34.0	39.6
6	6.44	6.8	13.2	19.6	25.9	32.3	38.7	45.1
7	7.38	7.6	14.7	21.8	29.0	36.1	43.2	50.4
8	8.34	8.3	16.2	24.0	31.9	39.8	47.7	55.5
Azimuth angle		0.52	1.04	1.56	2.08	2.60	3.12	3.64

Table 1g. Antenna Speed = 30 deg/s

*Width, m/s**		*Hits*						
		20	40	60	80	100	120	140
Met	*Eff*	*Number of effective independent samples*						
1	2.98	3.9	7.0	10.3	13.5	16.7	19.9	23.1
2	3.45	4.3	7.9	11.6	15.3	19.0	22.6	26.3
3	4.11	4.9	9.2	13.5	17.8	22.1	26.4	30.7
4	4.89	5.6	10.6	15.6	20.6	25.6	30.7	35.7
5	5.74	6.3	12.0	17.8	23.6	29.3	35.1	40.9
6	6.63	7.0	13.5	20.0	26.5	33.1	39.6	46.1
7	7.54	7.7	15.0	22.2	29.5	36.7	44.0	51.3
8	8.48	8.4	16.4	24.4	32.3	40.3	48.3	56.3
Azimuth angle		0.62	1.25	1.87	2.50	3.12	3.74	4.37

*Met = meteorological spectral width; Eff = effective spectral width, a result of antenna motion

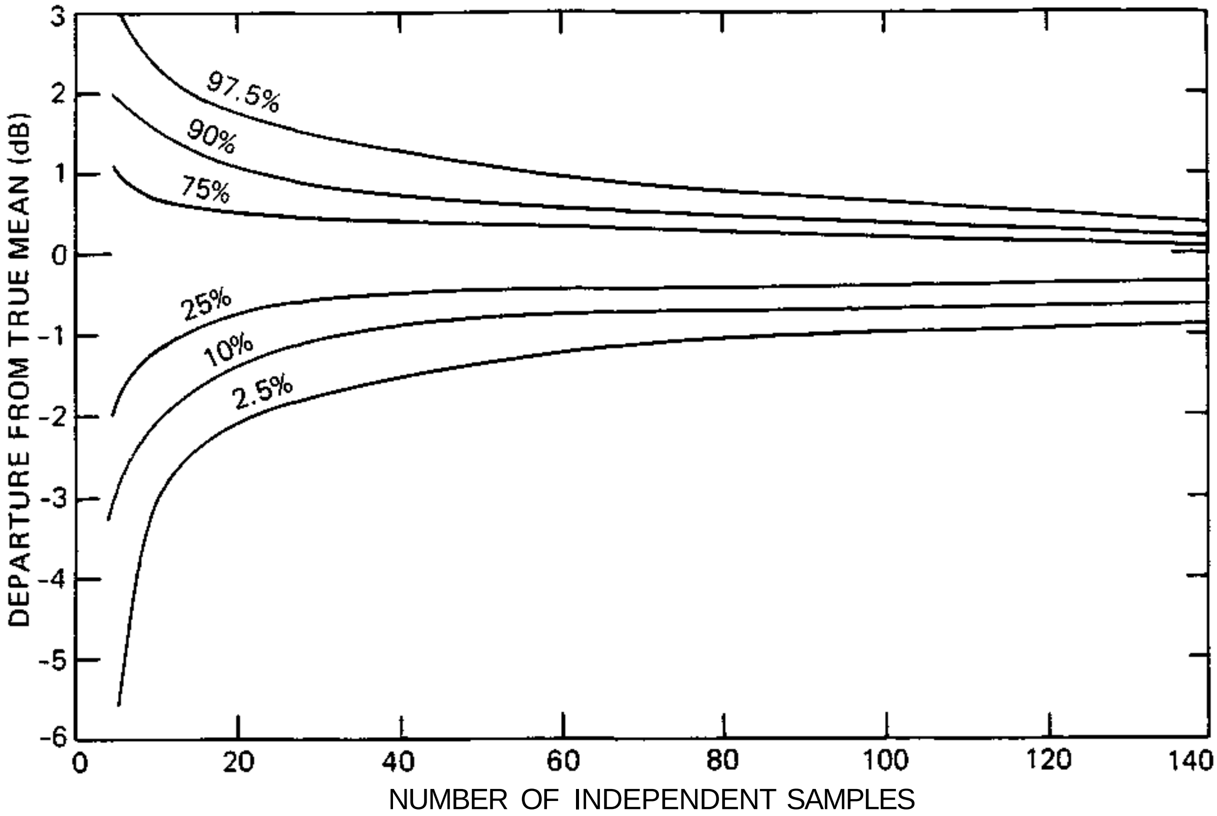

Figure 1. Widths of the distribution of the estimates of reflectivity in decibel departures from the true average reflectivity. Numbers on curves indicate the percentage of estimates greater than or less than the curve (for lines below 0 and above 0 respectively). (After Marshall and Hitschfeld, 1951)

Table 2. Number of Independent Samples Required
to Provide a Given Standard Deviation of the Estimate of Reflectivity*

Standard deviation	*Fractional part of S.D.*									
(dB), integer part	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
	Number of independent samples									
0.		1842	450	195	107	67	46	33	24	19
1.	15	12	10	8	7	6	5	4	4	3
2.	3	3	2	2	2					

*Note that since the distribution of the non-logarithmic reflectivity tends towards a normal distribution with large sample size, the use of a logarithmic standard deviation is not strictly correct.

4.2 Differential Reflectivity

The variable that generally restricts the rapidity of scanning is the differential reflectivity, Zdr. In a sense the differential reflectivity is the difference between the logarithms of two relatively large numbers, so one might expect that the estimate of Zdr requires greater accuracy in the estimates of the individual numbers than is required when either of the numbers is used individually (e.g., the reflectivity, which is one of the numbers in question, is usually not required to an accuracy of 0.05 dB). This then requires the longer averaging time. Sachidananda and Zrnic (1985) examined the required scanning speeds to provide different accuracies in Zdr. The assumptions made are similar to those made in the above discussion of reflectivity estimates. No correction is made for changes to the width of the doppler spectra due to antenna movement, but these differences do not produce a significant difference in the accuracies. Figures 2a and 2b, taken from the above report, show the results for parameters of a radar very similar to the CHILL system. The difference between the two figures is the correlation at time lag of zero between the horizontally and vertically polarized reflectivity of the scatterers. It is likely that in all cases the true value of this parameter lies between those shown in the two figures and in most cases is more nearly that shown in figure 2b than that in figure 2a. In estimating Zdr, the most desirable situation occurs if the individual H and V pulses are completely correlated.

The CHILL system is capable of obtaining Zdr in two different data gathering schemes. One method uses a polarization sequence of HHHV, where H represents a horizontal transmission and V a vertical transmission. In this mode of operation, the Zdr is computed between the last vertical and the first horizontal of the next group, and thus the correlation from H to V is the same (i.e., there is but one PRT between the two measurements) as if the sequence of HVHV were utilized. The exception is that there is one pair (first H and last V) that are totally uncorrelated. The other sequence that has been implemented is the alternating sequence of HVHV. It is this sequence for which Sachidananda and Zrnic have computed the standard errors given in figures 2a and 2b. Thus even though the number of pairs in a given time when using the HHHV procedure is one-half the number that would be used in an HVHV sequence, the number of independent samples would not be a factor of 2 more in the HVHV sequence because of the lack of independency between pairs. When these figures are used to estimate the accuracy of measurement and the scan rates, the effective number of pairs when operating in the HHHV mode should be increased by a factor of less than 2. The amount less than 2 is not clear, but a value of 1.5 is recommended as a first estimate.

In general, estimates of Zdr are required to be accurate to within 0.1 dB to be useful for rainfall estimates. It may be that some useful Zdr data can be used for water-phase determination with somewhat poorer reliability. To obtain better than 0.1 dB accuracy requires on the order of 100 sample pairs (figure 2a). This in turn requires 200 PRTs or 0.2 seconds for the sampling time. If the antenna is to move only one beam width in this time, the antenna speed must be 5 deg/s. This has been the speed at which most of the useful Zdr data has been gathered.

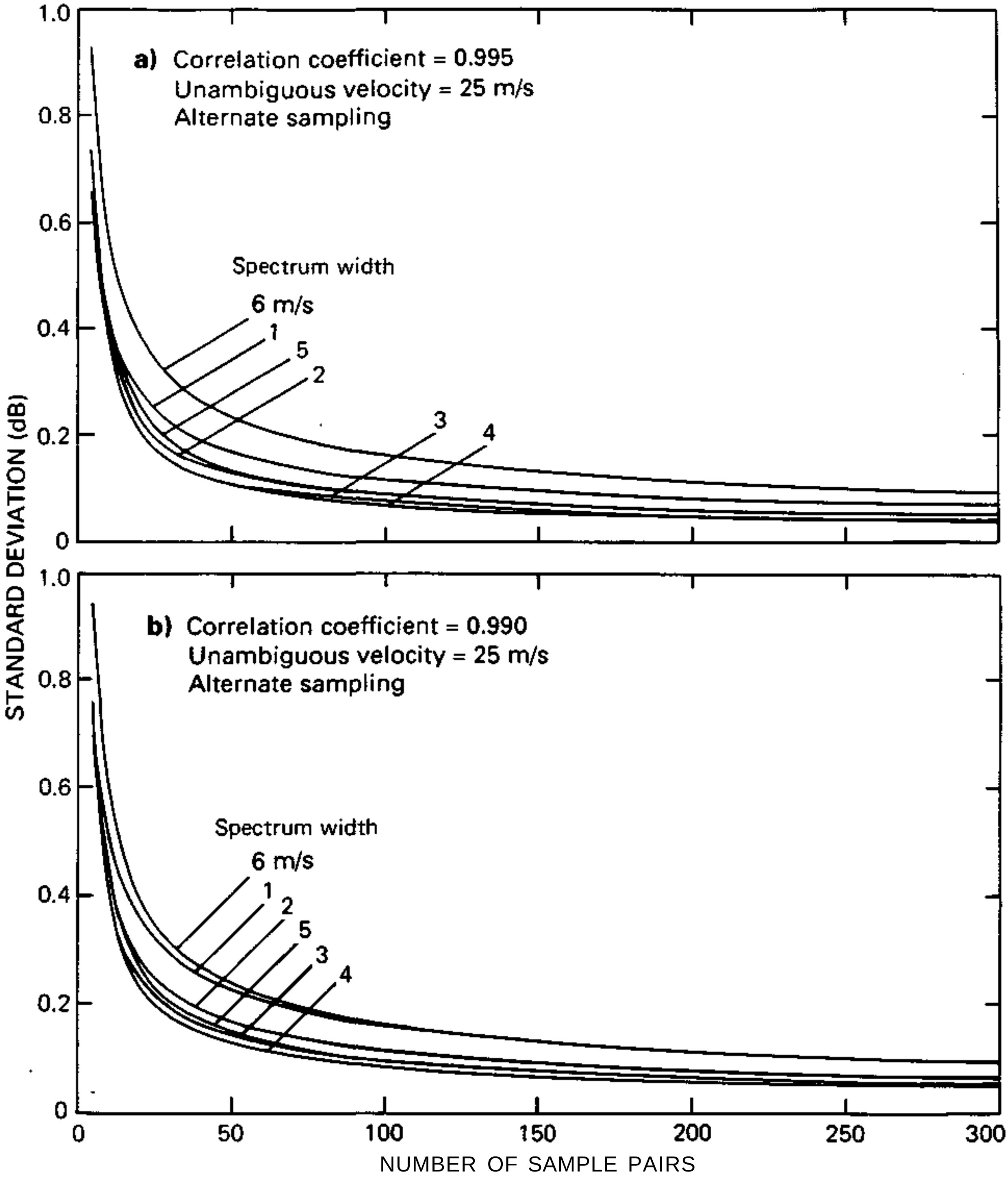

Figure 2. Standard deviation versus number of sample pairs for alternate sampling method (After Sachidananda and Zrnic, 1985)

If one can use a reduced range resolution, the accuracy can be improved considerably by range averaging. If this is done properly, the standard error of estimate decreases inversely as the square root of the number of range intervals added. In the CHILL system, this range averaging can be performed without necessarily reducing the range resolution by decreasing the pulse width to 75 meters (m) or even to 37.5 m. However, each of these reductions will produce a loss of sensitivity. The second method is to give up some of the range resolution and have range averaging over 300 m or larger ranges.

If a resolution of 600 m is considered, the number of samples can be increased by a factor of 4 (from the 150-m sample size) by range averaging, and if the antenna speed is increased by a factor of 4 to 20 deg/s and the sampling time (HITS) is reduced by a factor of 4 to a value of 50, nearly the same accuracy of 0.1 dB will be maintained, as well as the same angular resolution. The reporting resolution of 1 degree provides a spatial resolution of 600 m at a range of about 35 km. Other compromises are also possible; for instance, one could average 2 range samples and change the antenna speed by a factor of 2 with accompanying sample time change and produce similar accuracies with different resolutions.

In the alternate procedure, by paying a penalty of 6 dB in overall sensitivity, the pulse width could be decreased to 0.5 microsecond (range resolution changed to 75 meters). The sensitivity reduction is brought about by the reduced transmitter power of 3 dB and, assuming matched filter conditions, an increase in noise of 3 dB. Then after the samples are taken, range averaging can be done, which will return the range resolution to 150 meters and double the number of independent samples in the estimate of both Zdr and the other variables. In all cases, it is blithely assumed that the parent populations of the scatterers remain unchanged (i.e., homogeneous) over the increased sampling distances.

As a note, the CHILL system's receiver analog-to-digital converter presently samples every 0.25 microsecond. These samples are averaged to form a single measurement that occurs every 1 microsecond. It should be noted, however, that this averaging is of a different type in that the I and Q are averaged separately and do not permit independent measures for statistical variance reduction in estimates of either reflectivity or differential reflectivity. Since the noise is independent in these two samples, the noise reduction does take place and effectively is the means utilized to more nearly approach a matched receiver bandpass filter.

4.3. Mean Velocity

The final variable considered here is the estimate of mean velocity. Table 3 shows the standard errors of the estimates of the velocity as a function of the spectral width and the time of the sample measured in PRTs. In the case of velocity estimation, the signal-to-noise ratio (SNR) is also important in the calculation; thus there are tables for SNRs of both 0 dB and 15 dB. There is little change in the accuracy of the estimate for higher signal-to-noise ratios.

Table 3. Standard Deviation of the Estimates of Velocity
as a Function of Spectral Width and Number of PRTs in a Computation Group*

Table 3a. Signal-to-Noise Ratio of 15 dB

	Number of PRTs in sample						
Width, m/s	40	60	80	100	120	160	200
	Standard deviation, m/s						
1	.94	.77	.67	.60	.54	.47	.42
2	1.18	.96	.83	.74	.68	.59	.53
3	1.40	1.14	.99	.89	.81	.70	.63
4	1.66	1.35	1.17	1.05	.96	.83	.74
5	1.98	1.61	1.40	1.25	1.14	.99	.88
6	2.35	1.92	1.66	1.49	1.36	1.18	1.05
7	2.59	2.11	1.83	1.64	1.49	1.29	1.16

Table 3b. Signal-to-Noise Ratio of 0 dB

	Number of PRTs in sample						
Width, m/s	40	60	80	100	120	160	200
	Standard deviation, m/s						
1	2.65	2.17	1.88	1.68	1.54	1.33	1.19
2	2.65	2.17	1.88	1.68	1.54	1.33	1.19
3	3.35	2.74	2.37	2.12	1.94	1.68	1.50
4	3.53	2.88	2.50	2.23	2.04	1.76	1.58
5	3.79	3.09	2.68	2.40	2.19	1.89	1.69
6	4.40	3.59	3.11	2.78	2.54	2.20	1.97
7	4.65	3.79	3.29	2.94	2.68	2.32	2.08
8	5.07	4.14	3.59	3.21	2.93	2.54	2.27

* After Zrnic, 1975

Note: It is assumed that every pair is used in the computation.

The velocity can also be estimated in the two polarization modes discussed earlier. In the HHHV mode, the CHILL SP-20 program uses only the first pair of Hs in the computation of the first lag correlation. In this case, there is only one pair used for every four PRTs. For all but the widest of spectrum widths, the other three samples will be well correlated with the first. Nonetheless, a loss in accuracy is to be expected if the table is entered directly with the number of PRTs in the sample (total). An effective reduction of about 2 is recommended as a convenient rule of thumb. Thus, as an example, if the HHHV mode is utilized and 80 PRTs are in the total sample, a standard deviation in the velocity might be estimated as given by table 3a when entered with the PRT number of 40, yielding a 1.66 m/s standard deviation for a 4 m/s spectral width.

In the HVHV mode, a slightly different calculation algorithm is required. This algorithm uses all of the transmissions, but in a different manner.

The standard error of the estimate is likely to be nearly the same as for the standard pulse pair algorithm, since for a sufficiently large number of samples the variance of the estimate is dominated by the decorrelation time and total sampling period.

5. Data Recording Considerations

One of the larger expenses that will be incurred by the user is for the magnetic tapes that are expended during a project. The CHILL radar system offers a great deal of flexibility in the number of variables that are recorded. Tape usage also varies with the number of range gates recorded and the sampling period. These variables can be manipulated to provide considerable savings in tape without loss in the data desired. Thus a tape costing about $25 can be filled in about 40 minutes, or it can hold more than three hours of data.

There is presently a choice of recording the following variables: velocity, spectral width from either of two algorithms, differential reflectivity, and the correlation function with lags of one and two PRTs. All of these variables can be recorded with or without a preliminary pass through a ground clutter cancellation filter, or (except that the total data rate may be exceeded) can be simultaneously recorded with and without the filter. Additional variables will be computed on an as-desired basis. Among these will be the differential phase shift and a velocity calculated from the HVHV sequence. The power in the 10-cm channel (reflectivity) and the normalized coherent power (NCP, the correlation function of lag 1 normalized by the power in the same interval) are always recorded without choice. Additionally, under different modes of operation, the time series of the original data can be recorded for a limited number of range gates. Table 4 indicates the number of bytes required for each of these variables for each gate in the recording.

Table 4. Number of Bytes Required for Recording of Variables

Variable	*Number of bytes*	*Recording precision*
Power	1	.375 dB
NCP	1	3.906 e-3 (3/64)
Velocity		3.906 e-3 of a full Nyquist interval (0.207 m/s prt=l ms)
Width (both algorithms)	1	3.906 e-3 of a full Nyquist interval (0.207 m/s PRT=1 ms)
Differential reflectivity	1	46.9 e-3 dB (3/64 dB)
Correlations (both lags) and time series	4	Real and imaginary parts as upper two bytes of a 32-bit floating point number of sign and 8-bit exponent and 7-bit fraction
Differential phase	1-2	To be decided

The number of gates recorded influences the tape usage. This number can be controlled in several ways. First, if the maximum range of interest can be specified, this limit can be applied to the maximum number of gates recorded. Second, range averaging can be applied, which in effect reduces the number of range gates recorded by the factor of the reduced resolution. Third, there is a pre-programmed procedure that limits the number of gates as a function of elevation of the radar beam. Thus, when the variable "maximum tops" is set, whenever the beam exceeds this height the recording is terminated for that particular ray. At the higher elevation angles, this procedure can be surprisingly effective in limiting the amount of tape usage.

The amount of tape that the maximum top limitation can save is easily computed by considering the fraction of the total time that the sample points remain above the maximum height. This was performed for a number of cases, and the results follow. If the elevation increment is 1 degree, and the starting elevation is 0.5 degree with the upper elevation angle limit set to 10.5 degrees and a maximum top of 50 thousand feet (kft), the saving will be 5.6% of the usage for full recording to 150 km. With the same parameters except for 40 kft maximum top, a saving of 23% will be realized. If the maximum elevation angle is increased to 20.5 degrees at 50 kft, a savings of 32.5% occurs, and with 40 kft, a savings of 40% occurs. This is a good savings, especially when higher angles are scanned.

An estimate of the time that a tape will last during recording can be made from the following formula:

$$\text{Time (min)} = 2.6\ 10^{6} * \text{Integration time (s)} \div \text{number gates} \div \text{number bytes per gate}$$

6. Example: Design of a Scanning Procedure

During the design of scanning procedures, the observational requirements of the echo systems of interest must be considered along with the factors presented in the preceding sections. Two important meteorological parameters are the expected time rate of change of the echoes under study and the atmospheric volume that they typically occupy. For example, scans that are repeated every 15 minutes may be adequate for stratiform precipitation, but too infrequent for active convection. Boundary layer studies may require full PPI surveillance of the first few kilometers of the troposphere, while thunderstorm echoes with limited horizontal extent may reach the lower stratosphere.

The anticipated analysis procedures are another obvious source of constraints on data collection schemes. A common analysis step is interpolation of the data to a three-dimensional Cartesian grid. Voids may appear in these arrays if the original data has insufficient spatial density. The following example is provided to illustrate several of the considerations that must be balanced in designing a scanning procedure.

Assume that it is desired to collect reflectivity, mean velocity, and differential reflectivity data through the full volume of thunderstorm echoes every 2.5 minutes. The desired standard error limits for these data fields are 1.5 dB, 1.2 m/s, and 0.15 dB, respectively. Assume also that the use of a PRT of 1040 microseconds (e.g., maximum unambiguous range of 156 km and velocity of 26.42 m/s) is satisfactory.

The first step is to determine the number of PRTs necessary to maintain the desired error standards. Table 2 shows that only six independent samples are required to meet the reflectivity measurement accuracy. With a 4 m/s spectrum width and a 15-dB SNR, table 3a indicates that approximately 50 PRTs are needed for a 1.2 m/s standard deviation in the velocity estimate. With an HHHV polarization sequence some 20 pairs of H and V are required to hold the desired Zdr accuracy (30 pairs, from figure 2, divided by 1.5, the factor due to the HHHV vs HVHV pattern). To obtain the desired 20 pairs requires 80 PRTs. In comparison, if a sequence of HVHV is chosen with the same accuracies, 30 pairs are required and this is obtainable with 60 PRTs. Thus the HHHV procedure does require a bit more time. The advantage of the HHHV sequence is historical (i.e., it was the first method used to satisfactorily combine Zdr and doppler measurements), and the standard deviations of the estimates have been theoretically derived. These estimates of errors for the HVHV sequence are not available.

The hit number requirement imposed by the Zdr standard error is the most stringent, so if the HHHV procedure is selected, the value of HITS (number of PRTs required) must be 80.

The second step is the choice of the antenna azimuth rotation speed. If it is desired that estimates from the 80 PRTs be output once per degree of antenna rotation, then from equation 5 the antenna speed must be 12 deg/s, which may be too slow to scan the storm volume in the desired time. As discussed earlier, averaging of pairs of range gates will permit the number of PRTs to be halved and the antenna speed to be doubled. If the resultant decrease of range resolution from 150 m to 300 m is tolerable, then a 24 deg/s antenna speed can be used.

Once the antenna speed is known, the number of sweeps that can be made in the desired volume scan duration may be estimated. Assuming that a 120-degree-wide sector will likely cover the storms of interest, the basic time needed to sweep across the sector is 5.0 s at the 24 deg/s rate. However, additional time is necessary to reverse the antenna rotation at the ends of the sector. For the CHILL system, a nominal value for antenna acceleration is 10deg/s*s. Since one acceleration/deceleration pair occurs in each sweep, the time adjustment is 2 times the antenna speed, 24 deg/s, divided by the acceleration, 10 deg/s*s, which yields an additional time of 4.8 s. Thus, the net time for each sweep will be approximately 10 s. An additional time margin of some 10 s is necessary to reposition the antenna at the end of each volume scan in order to be ready to begin the next one; so out of the 2.5-minute volume, 140 s are available for scanning. Since 10 seconds are required per sweep, 14 sweeps can be made within each 2.5-minute volume scan.

The size(s) of the elevation angle steps used between these sweeps will limit the maximum echo height that may be observed. If 1-degree steps are used starting from a 0.5-degree minimum, the maximum elevation angle will be 14.5 degrees. At a range of 45 km, equation 1 shows that at this elevation angle the beam height will be 11.4 km, which will probably be adequate for the observation of many thunderstorm echo tops. However, at a range of 15 km the beam height is only 3.8 km with a 14.5-degree maximum elevation angle. For observations at these shorter ranges, some scan modifications are worth consideration. One possibility is to reduce the width of the scan sector, since less time will be required to sweep across the smaller region. A second means to raise the maximum elevation scanned is to increase the elevation angle step size.

The CHILL antenna control program contains an elevation step optimization scheme that allows larger elevation angle increments to be used while preserving a user-specified maximum vertical separation between successive sweeps at ranges of interest. This maximum separation standard is applied at the outer boundaries of a user-defined analysis region, as shown in figure 3. Continuing the present example, assume that a maximum beam separation of 1.75 km can be tolerated while scanning ranges less than 45 km up to a height of 12 km. Based on these specifications, the optimizer would program the sequence of elevation angles given in table 5.

It is apparent that for *short-range* observations the step optimizer allows a given number of elevation angles to scan significantly greater heights while preventing excessive separations between sweeps. In the current example, 14 sweeps would be maintained during each 2.5-minute volume scan with the transition from fixed 1-degree elevation steps to variable optimized steps occurring when the 14.5-degree maximum elevation angle could no longer reach the echo tops.

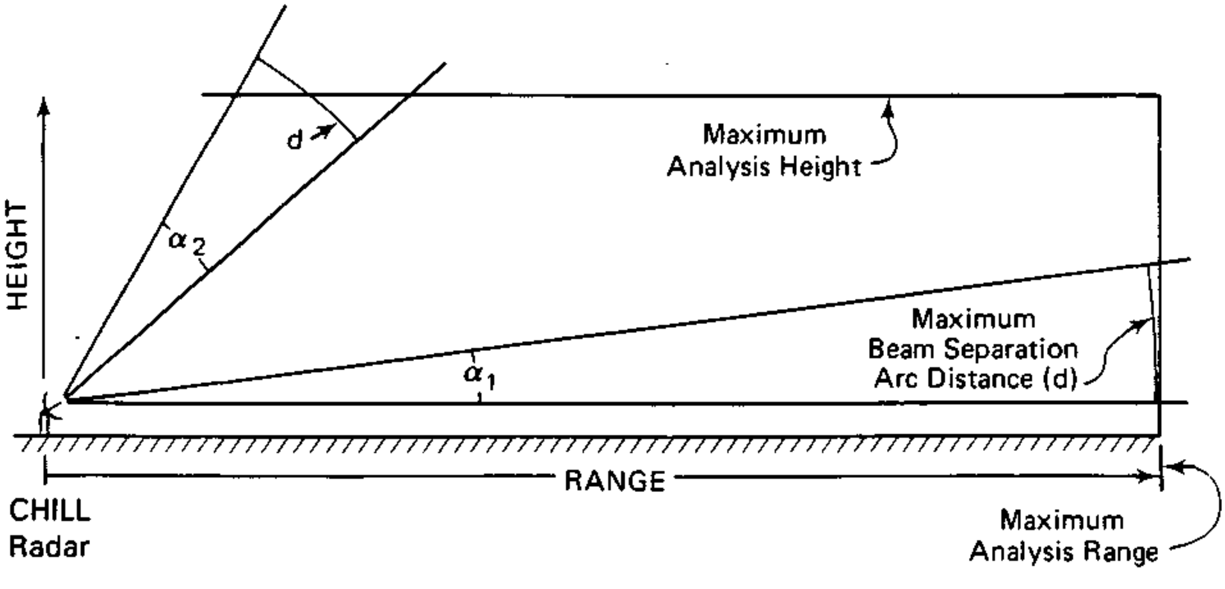

Figure 3. Elevation step optimizer geometry. Note that as slant range decreases, the elevation angle step size (a) required to conserve the maximum tolerable beam separation distance (d) increases (i.e., $\alpha_2 > \alpha_1$).

Table 5. Example of Angles from the Scan Optimizer

Sweep no.	*Elev angle (deg)*	:	*Sweep no.*	*Elev angle (deg)*
1	.5	:	8	18.24
2	4.95	:	9	20.87
3	7.17	:	10	23.87
4	9.38	:	11	27.27
5	11.58	:	12	31.11
6	13.76	:	13	35.43
7	15.92	:	14	40.27

Real-time considerations during data collection often force modifications upon even the most carefully pre-designed scanning procedures. However, the use of this document to prepare data collection strategies should produce a good starting point for the conduct of field operations.

7. Data Recording Format

The CHILL data format was revised in 1986 with the installation of a major hardware upgrade. Data is recorded on 6250 character-per-inch 9-track magnetic tape in variable length blocks that may be as large as 16,896 bytes. Each block consists of one or more logical records (hereafter referred to simply as records).

The first two characters (ASCII) of each record are used to identify the record type. Currently there are two types of records: "CD" records, which contain one ray's data; and "CU" records which contain supplemental housekeeping data in "Universal Format". A "Cc" record contains comments entered by the radar operator. The second two bytes of each record form a 16-bit number which is the (16-bit) word count for the record. This word count includes both the record-type and record-length words. Note that unless otherwise indicated, all of the 16-bit words go on the tape using the VAX-style little-endian packing, where the least significant byte appears before the most significant byte. If records contain any one-byte-data words, there will always be an even number of items, so that records and fields will always begin on a 16-bit word boundary.

7.1. "CD" Record Format

The CD data format consists of a variable-length housekeeping section followed by one or more data fields. Each data field starts with a two-character (ASCII) field identifier. This is followed by a two-byte binary integer, which gives the field length in 16-bit words (including the length of the field header). The contents of each of the field headers are listed in a subsequent section. The structure (C-language), shown in table 6, defines the layout of the CD housekeeping headers. Shorts are 2-byte binary integer numbers (2's complement unless otherwise noted), and chars are ASCII character arrays.

Table 6. "CD" Records: Housekeeping Layout

Word offset	*Item type*	*Comment*
0	char btype[2];	record type code "CD" for data record, "CU" for extended (UR) hsk record, "Cc" for comment record. This structure describes the "CD" records.
1	short hsklen;	record length in 16-bit words (includes hsklen and btype)
2	short offsetl;	number of 16-bit hsk words that follow before the first data header
3	short az;	antenna azimuth 360/4096 degrees/count
4	short el;	antenna elevation 360/4096 degrees/count
5	unsigned short raynum;	ray number, within volume scan (reset to 1 at start of each volume)
6	short hour,min,sec,tenths;	time
10	short antstat;	antenna status flag masks, bit values:
	#define CW 1	on -> clockwise rotation
	#define SECTOR 2	on -> sector scan mode
	#define REC 4	on -> recording enabled
	#define ZDR 8	on -> zdr recorded
	#define R1REC 0x8000	on -> Rl recorded
	#define R2REC 0x4000	on -> R2 recorded
	#define MAN 0x100	on -> manual pos. mode
	#define RHI 0x80	on -> RHI scan mode
11	short year,month,day;	date
14	short volnum;	volume scan number, starts with volume 1, continues incrementing throughout data collection period.
15	short sweepnum;	sweep number, reset to 1 at beginning of each volume.

Note: As of January 1989, the housekeeping section may terminate at this point (as indicated by word 2 - offsetl) on most records. On the first few records after the start of a scan sequence, the housekeeping section will continue. On data recorded before January 1989, the housekeeping section ran through word 22 (hits) and was of constant length.

Table 6. Continued

Note: all angles are reported as 12-bit fractions of a circle; i.e., multiply by 360.0/4096.0 to get degrees.

16	short azprogpos;	programmed position - this is the azimuth angle the antenna is holding in either RHI or manual modes.
17	short elprogpos;	programmed position - this is the elevation angle the antenna is holding when in the PPI or manual modes.
18	short azcwlim;	right az sector limit
19	short azccwlim;	left az sector limit
20	short prt;	transmitter pulse repetition time in microseconds
21	short swprate;	antenna sweep rate in deg/sec* 100
22	short hits;	the number of transmit pulses per SP20 major cycle
23	short scanmode; 0 -> PPI 1-> RHI 2-> MANUAL (both az and el) 3 -> PPIMAN (az in PPI mode, el in manual mode) 4 -> RHIMAN (el in RHI mode, az in manual mode) 5 -> IDLE (antenna control disabled) 6 -> SEEK (antenna moving to desired position) 7 -> HOLD (antenna holding "programmed" position) 8 -> RHIHOLD (same as 7, but RHI mode set)	antenna scan mode:
24	short pulse_len;	transmit pulse length in nanoseconds
25	short gate_space;	range gate spacing in nanoseconds
26	short txbin;	range gate offset to transmitter pulse; tx pulse occurs at range 0 which is not necessarily the first gate in the data array txbin locates range 0.
-27	short maxtop;	maximum height of data recording; 0-> no limit.
28	short el_up;	elevation up scan limit

Concluded on next page

Table 6. Concluded

29	short el_down;	elevation down scan limit
30 (byte 1)	char bypass;	1 -> polarization switch is bypassed, giving horizontal polarization only
30 (byte 2)	char step_opt;	1 -> elevation step optimizer is enabled
31	short opt_rmax;	step optimizer - maximum range of interest in km* 100
32	short opt_htmax;	step optimizer - maximum height of interest in km* 100
33	short opt_res;	step optimizer - desired spatial resolution in meters
34	short filt_end;	the number of clutter filtered gates
35	short filt_num;	ID number of the current clutter filter
36	short nyqvel;	the Nyquist velocity in m/sec*256
37	short qual;	reserved for quality check flag
38	short spare;	currently unused word

The following three items are null terminated ASCII strings:

39	char segname[8];	current scan segment name
43	char sp20prog[8];	SP20 signal processor program name
47	char polseq[8];	polarization sequence (may be truncated) H -> Horizontal transmit and receive V -> Vertical transmit and receive X -> Horizontal transmit, vert receive Y -> Vertical transmit, horizontal rec

——————End of "CD" housekeeping information——————

7.2. CD Records: Data Field Headers

Immediately following the housekeeping section, there will be one or more data fields. Each data field begins with a short header that describes the data type and format. The first word of the header contains two ASCII characters that specify the field type. The second word is the field length (in 16-bit words). All of the possible field types are discussed below. Word offsets listed are with respect to the start of the field header.

7.2.1. 1986 Received Power Fields

The fields described in table 7 were used in 1986 before the SP20 was delivered. The only data available that season was 512 gates of received power.

Table 7. 1986 Field Description

Word offset	*Item type*	*Comment*
0	char ftype[2];	"DM" rec. power field identifier
1	unsigned short lrecl;	number of 16-bit words in this field
2	short thresh;	(not used)
3	short mapnum;	(not used)
4	unsigned short maps[4];	(not used)
7	unsigned char vid[512];	512 bytes of data

7.2.2. 1987 and Later Received Power Fields

This field is always recorded unless the SP20 is operating in a pure time-series data-collection mode.

Table 8. 1987 Field Description

Word offset	*Item type*	*Comment*
0	char dtype[2];	"IP" field code
1	unsigned short lrecl;	number of 16-bit words in this field
2	short gates;	number of gates recorded
3	short numhed;	number of header words (typically 8)
4	short format;	numeric representation; code=l implies data words are 8-bit unsigned
5	short thresh;	threshold used for data compression
6	short irb;	initial range bin recorded
7	short token;	sp20 token (not used)

This is followed by the number of unsigned bytes specified by the difference between the "gates" parameter (word 2) and the "irb" parameter (word 6). The range of the first gate is given by "irb". Each byte may be used to index the receiver calibration function array to obtain the received power (see the calibration notes in the CHILL operations guide, to be published later this year as Illinois State Water Survey Miscellaneous Publication 110).

7.2.3. Differential Reflectivity Fields (1987 and Later)

Table 9. 1987 and Later Reflectivity Fields

Word offset	*Item type*	*Comment*
0	char dtype[2];	"DR" field code (zdr)
1	unsigned short lrecl;	number of 16-bit words this field
2	short gates;	number of gates recorded
3	short numhed;	number of header words (typically 7)
4	short format;	numeric representation code=2 implies data words are 8-bit 2's complement numbers with an offset of-64
5	short irb;	initial range bin (typically 0)
6	short offset;	calibration + 64 = term subtracted from zdr values before recording

This is followed by the number of signed bytes specified by the difference between the "gates" parameter (word 2) and the "irb" parameter (word 5), with the range to the first gate given by "irb". Each byte should be treated as a 2's complement number. The units are 3/128ths of a dB. This gives a 12-dB range that is offset -3 dB since large negative values are not expected. So to reconstruct a zdr value from one of these bins:

$$ZDR = (bin + 64) * 3.0/128.0$$

7.2.4. Correlation Fields: R1 and R2 (1987 and Later)

During the 1987 and 1988 field operations, the SP20 was not able to calculate the end product fields such as velocity and spectral width. In lieu of these, the complex lag correlation fields Rl and R2 were optionally recorded. Since two 16-bit floating point numbers were recorded for each gate, these fields take up a large amount of space on tape. Consequently, these fields were generally not used after November 1988, when SP20 software to generate velocity and width fields was developed.

Table 10. Correlation Fields

Word offset	*Item type*	*Comment*
0.	char dtype[2];	"R1" or "R2" field identifier
1	unsigned short lrecl;	number of 16-bit words this field
2	short gates;	number of gates recorded
3	short numhed;	number of header words (typically 6)
4	short format;	numeric format code=3 implies that data is complex floating point (see below)
5	short irb;	initial range bin

This is followed by the number of (real, imaginary) pairs specified by the difference between "gates" and "irb", with the first pair located at a distance given by "irb". Each real or imaginary number consists of the most significant 16 bits of a 32-bit IEEE floating point number. The correlations are not normalized by R0. The order of the data within the gate location is Rl real, Rl imaginary, R2 real, and R2 imaginary.

7.2.5. Mean Velocity Fields

Velocity fields were first generated by the SP20 in the fall of 1988. These fields could also be generated after the fact from Rl fields by the VAX data copy program. This program was used to copy and reformat data for outside users.

Table 11. Description of Mean Velocity Fields

Word offset	*Item type*	*Comment*
0	char dtype[2];	"VE" field code
1	unsigned short lrecl;	number of words this field
2	short gates;	number of gates recorded
3	short numhed;	number of header words (typically 6)
4	short format;	numeric representation code=4 implies data words are 8-bit with a 128-count offset
5	short irb;	initial range bin

This is followed by the number of bytes given by the difference between "gates" and the "irb", with the first byte representing a range given by "irb". Each byte represents an offset (unsigned) binary value such that:

velocity = (byte - 128)/128.0*Nyquist velocity

7.2.6. Spectral Width Fields

Spectral width was first generated by the SP20 in the fall of 1988. However, in some cases it was generated after the fact and written on data tapes in this format. Two width estimators are available. Fields identified as "Wl" fields were based on the lag 1 and lag 0 correlations with signal-to-noise ratio correction. Fields identified as "W2" fields were based on the lag 2 and lag 1 correlations.

Table 12. Description of Spectral Width Fields

Word offset	*Item type*	*Comment*
0	char dtype[2];	"W1 or W2" field code
1	unsigned short lrecl;	number of words this field
2	short gates;	number of gates recorded
3	short numhed;	number of header words (typically 6)
4	short format;	numeric representation code=4 implies data words are 8-bit with a 128-count offset
5	short irb;	initial range bin (typically 0)

This is followed by the number of bytes specified by the difference between the "gates"and the "irb", starting at a range given by "irb". Width is recorded as an unsigned offset binary such that:

spectral width = (byte - 128) * 0.25 m/sec

7.3. Aircraft Tracking Information

During field operations that involve research aircraft, beacon data from the FAA radars is telemetered to the CHILL system for real-time display. This information is also recorded on the data tape in the following format.

Table 13. Description of Aircraft Tracking Data

Word offset	*Item type*	*Comment*
0	char dtype[2];	"AP" field code (a/c track)
1	unsigned short lrecl;	number of words this field
2	char name[8];	name of first aircraft
6	short x;	East-west location of plane with respect to CHILL - in km. 128
7	shorty;	North-south location of plane with respect to CHILL - in km , 128
8	short alt;	altitude reported in 100s of feet
9	char name2[8];	name of second aircraft
13	short x2,y2;	location of second aircraft
15	short alt;	altitude of second aircraft
16	char name3[8];	name of third aircraft
20	short x3,y3;	location of third aircraft
21	short alt;	altitude of third aircraft

Note that this field is recorded on the tape whenever any one of the three aircraft are reported. It is therefore necessary to compare the position reports with the previous report to determine which aircraft have actually been updated.

7.4. Time Series Data

Time series data was first recorded in 1988. Currently when time series data is recorded, "TS" fields will be the only fields present. In the future, however, time series data for one or two gates may accompany the usual doppler fields.

Table 14. Description of Time Series Field

Word offset	*Item type*	*Comment*
0	chardtype[2];	"TS" field code (time series)
1	unsigned short lrecl;	number of words this field
2	short irb;	range to first bin (.25 microsec)
3	short gsp;	time between samples (.25 microsec)
4	short gates;	number of gates recorded per ray
5	short totsamp;	total number of samples per field
6	short nbytes;	sample size in bytes 4 or 8

This will be followed by "totsamp" samples of time series data. Each sample will be "nbytes" long. In-phase data will be followed by quadrature data. If "nbytes" is 8, each sample will consist of two 32-bit IEEE floating point numbers. If "nbytes" is 4, each sample will consist of two 16-bit words, each of which is the upper half of an IEEE floating point number.

7.5. CU Records

CU records are inserted into the data stream at the start of each sweep of the antenna. These are intended as an aid in converting the data tapes to Universal Format. The CU record is a section of housekeeping information in the "Universal Format" described by Barnes (1980) with certain new header words proposed by Oye and Mueller (1986). Exceptions to this are:

1) The first word is ASCII "CU" instead of "UF".

2) The second word is record length, but it has the VAX byte ordering. The rest of the record has IBM ordering.

3) All headers exist, but the data itself is absent. In the field headers, the pointers to the start of the data will be zero.

8. References

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