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Windshear Radar Calibration: Transmitter Power and Receiver Gain Stability

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I. INTRODUCTION

During 1991, the Antenna and Microwave Research Branch began its Windshear Radar Experiment flights onboard the Boeing 737 airplane owned by NASA Langley. Experiment team members used a radio frequency (RF) test set to check the radar transmitter power and receiver gain on the airplane before and after flights. This document contains the results of power measurements and gain and noise calculations done to characterize the radar stability over a period of months.

The RF test set was manufactured by IFR Inc. and shall be referred to here as the IFR test unit. The test unit performed two functions: it measured the radar transmitter power and provided known signal inputs to the radar receiver. Upon receiving the test signal inputs, the windshear radar recorded the automatic gain control (AGC) attenuation applied to the signal and the resulting in-phase and quadrature (I,Q) detected voltages of the signal. From those recorded values, receiver gain and receiver noise power have been calculated.

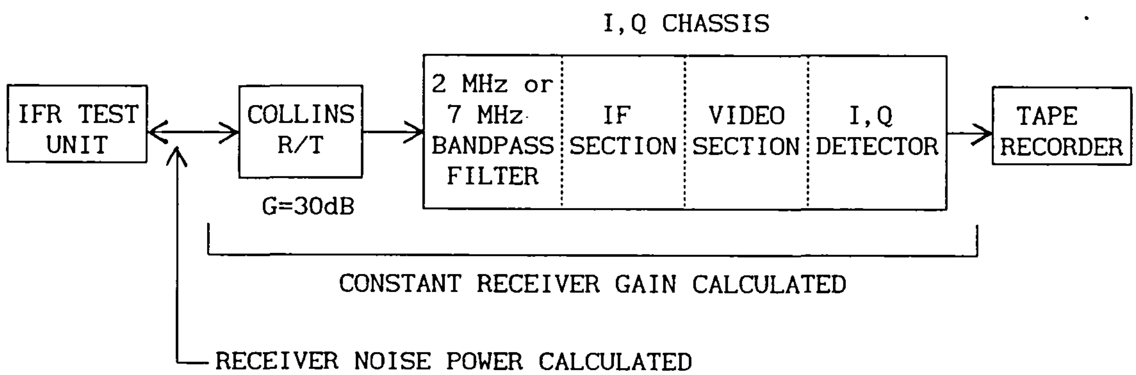

Figure 1.-Simplified block diagram of the Windshear Radar receiver showing the portions characterized by the system gain and noise.

Figure 1 shows major portions of the receiver system which are characterized by the gain and noise power calculations described here. The receiver gain is the gain of all of the receiver components following the antenna excepting the variable AGC attenuators. The gain should ideally be constant, but varies slightly from flight to flight due to temperature changes, connector changes, and component aging. It is calculated as

$$\text{GAIN} = \frac{(\text{I,Q POWER})(\text{AGC})}{(\text{IFR POWER}) + (\text{NOISE POWER})} \qquad (1)$$

where IFR POWER is the test signal power input to the receiver, AGC is the recorded attenuation applied to the signal in the I,Q chassis, and I,Q POWER is an average recorded power. Noise power is calculated as the effective noise seen at the receiver input. It can be assumed that most of the receiver noise is due to contributions by the receiver/transmitter (R/T) unit, since the gain of that unit was measured in the laboratory at 30 dB.

The 27 windshear flights conducted in 1991 are listed in Appendix A. During those flights, two research Collins weather radar R/T units, designated #1 and #2, were used interchangeably. The second unit had been purchased as a back-up R/T to be used in case the first unit failed. The same I,Q chassis was used on every flight. Calibrations were performed for both R/T units at wide (7 MHz) bandwidth and narrow (2 MHz) bandwidth settings. The radar was tested in various modes of operation which used different combinations of pulse repetition frequency, pulse width, number of range bins, and other radar parameters selectable by the operator. The radar modes are described in Appendix B.

For calibrations where the high power amplifier unit was switched on, a 10-dB attenuator was placed between the R/T unit and the IFR unit. The results of all of the calibrations are summarized in this document.

II. MEASUREMENTS WITH THE IFR CALIBRATION UNIT

For calibration purposes, an RDX-7708 test unit, manufactured by IFR Inc., was connected by a directional coupler to the line between the research R/T unit and the antenna. Figures 1 and 2 show the placement of the calibration unit in the radar system. Figure 1 is a block diagram, while figure 2 shows the waveguide connections from the antenna to the research R/T unit. Figure 2 also depicts the high power amplifier unit and the standard weather radar R/T unit which was available for the pilot's use, but was not calibrated by the Windshear Experiment team.

The IFR unit measured the power of the signal coming from the radar transmitter. At the same time, the calibration unit was externally triggered by the transmitter to generate a pulsed test signal to send back to the radar receiver. Table 1 below contains a partial list of IFR unit specifications [1].

Table 1.-IFR Calibration Unit Specifications

Peak power indicator display:
- Range: 40 through 250 W
- Accuracy: ±0.6 dB
- Resolution: 1 W

RF output frequency range: 9295 through 9425 MHz

RF output level:
- Range: -50 dBm through -127 dBm in 1 dB steps
- Accuracy: ±2 dB over frequency and attenuation range
- Repeatability: ±0.25 dB

Pulse modulation: Externally triggered PRF
- Range: 50 through 20,000 pps
- Manual pulse width range: 0.4 through 99.9 μs

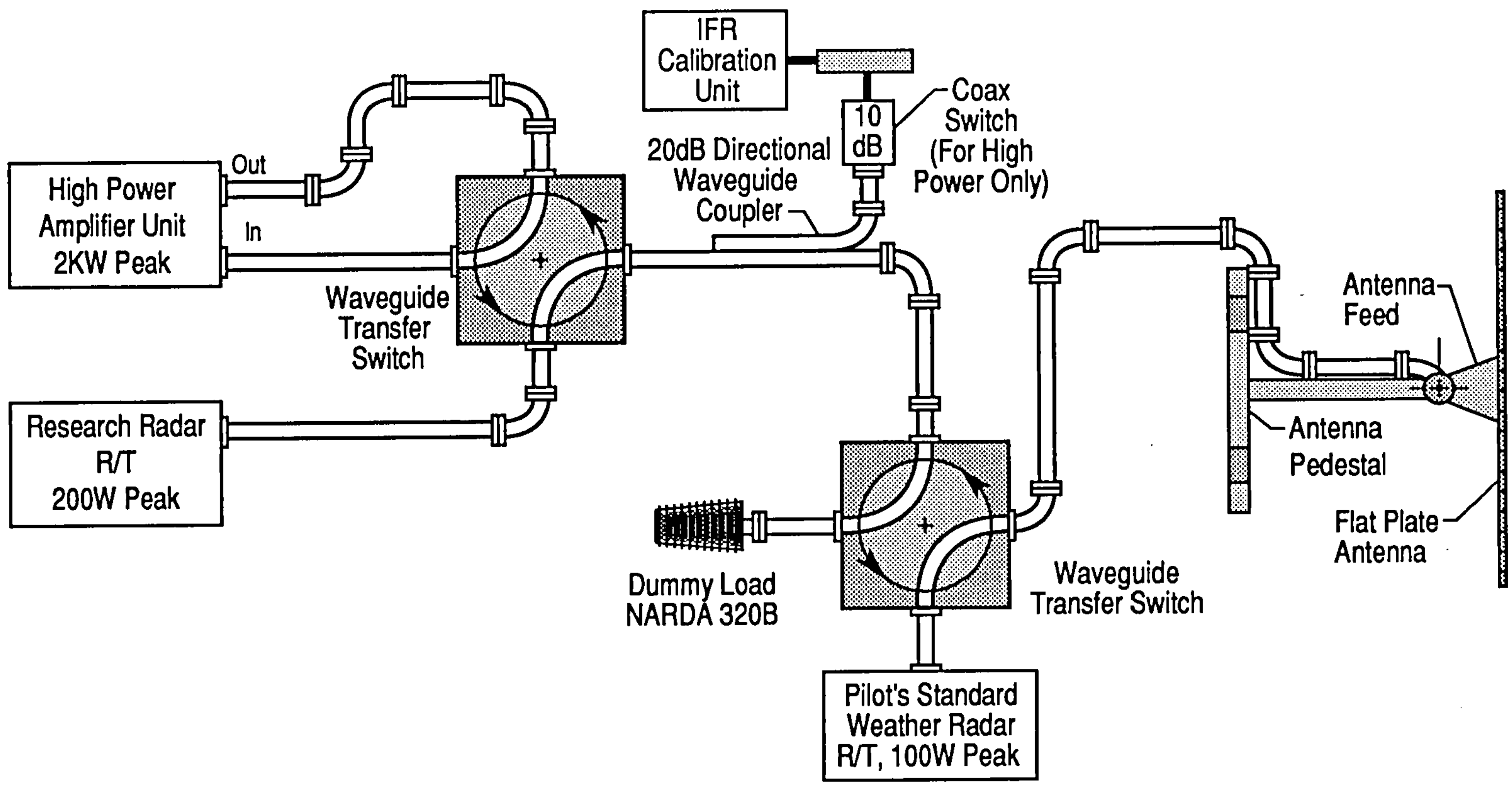

Figure 2.-Waveguide connection showing placement of the IFR calibration unit in relation to the research R/T unit and the antenna.

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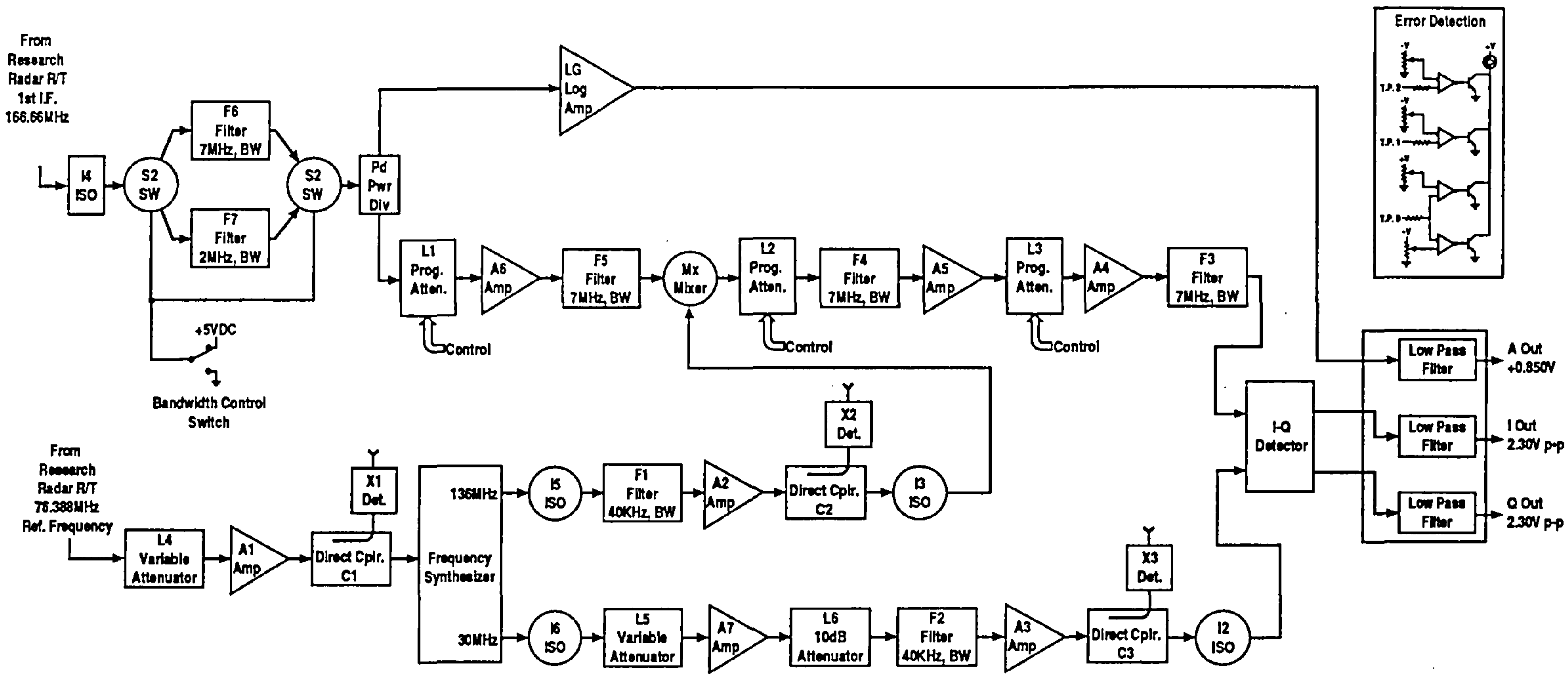

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Figure 3.-Signal flow diagram of the windshear radar receiver following the research radar R/T unit . The bandwidth control switch S2, located on the I,Q chassis, selects between wide BW (7MHz) and narrow BW (2MHz).

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The IFR or calibration input power was usually set at -127, -105, -60, and -50 dBm in sequence; the power was held constant at each level for at least 10 seconds. The R/T unit number, selected IFR power settings, IRIG-A time, and measured transmitter power were noted in handwritten flight logs. I,Q voltages, AGC attenuator settings, receiver bandwidth, and IRIG-A time were recorded on magnetic tape during calibrations, just as during the flight experiments. Calibration recordings were made before most Windshear Experiment flights and after some of the flights.

Calibrations were usually performed at both "wide" and "narrow" receiver bandwidths. Figure 3 shows the portion of the receiver where the bandwidth control switch S2 is located. Located in the I,Q chassis, the switch selects either a 7 MHz filter, for "wide" bandwidth, or a 2 MHz filter, for "narrow" bandwidth. Also shown in figure 3 are attenuators A4-A6, whose combined attenuation is set by the AGC system to keep the detected I,Q voltages around 2.3 volts peak-to-peak. The recorded attenuation and the I,Q values were used in the gain and noise calculations described in the following section.

III. CALCULATIONS

The following section describes how receiver gain and noise power were calculated from the recorded data.

A. Receiver Gain

Gain was calculated from AGC attenuation data and I,Q voltage data recorded when the IFR power had been set at -50 dBm, which was much higher than the expected receiver noise power of -108 dBm. Since the noise power was not significant relative to the test signal input, the gain could be determined without knowledge of the exact noise power. For each gain calculation, the mean AGC attenuation and I,Q power were computed for 3 sets of 50 samples. I,Q power is defined as

$$(\text{I,Q POWER})_{\text{watts}} = \frac{\left(I_{\text{volts}}\right)^2 + \left(Q_{\text{volts}}\right)^2}{50 \text{ ohms}} \tag{2}$$

where 50 ohms is the assumed load resistance.

Gain was calculated using the mean AGC and I,Q values in the equation

$$\text{GAIN} = \frac{(\text{I,Q POWER})(\text{AGC})}{(\text{IFR POWER})} = \frac{(\text{I,Q POWER})(\text{AGC})}{1\text{ E-5 mW}} \tag{3}$$

The results from the three sets of samples were averaged to obtain a gain for each calibration. Those results were further averaged to show variations in gain according to R/T unit number, receiver bandwidth, radar mode, and time.

B. Receiver Noise

Receiver noise power was calculated using the average computed gains together with the AGC attenuation data and I,Q data recorded when the IFR power had been set at -127 dBm, well below the noise level. Using the assumption that most of the noise was added to the signal before most of the gain, noise was calculated by rearranging equation 1 into the form

$$\text{NOISE POWER} = \frac{(\text{IQ POWER})(\text{AGC})}{\text{GAIN}} - (\text{IFR POWER}) \tag{4}$$

$$= \frac{(\text{IQ POWER})(\text{AGC})}{\text{GAIN}} - 1.995\ \text{E-13 mW}$$

Noise power was calculated from each calibration data set and then averaged to provide averaged receiver noise power for both R/T units and both bandwidths.

C. Checking the Gain and Noise Calculations

To check the results of the gain and noise calculations, gain was calculated using the average noise power together with AGC attenuation data and I,Q voltage data recorded for the range of IFR input powers between -127 dBm and -50 dBm. The same gain should result from each calculation, regardless of IFR input power.

IV. TABULATED RESULTS

The choice of radar mode did not affect any calibration results except in the case of mode 1, which produced a noticeably lower transmitted power than any of the other modes. Table 2 below outlines the characteristics of mode 1 and mode 6 [2] and lists an average value for the peak power transmitted in each mode. Other modes that were tested during calibration recordings produced transmitted powers, receiver gains, and receiver noise powers very similar to mode 6, the most commonly used mode.

Table 2.-COMPARISON BETWEEN MODE 1 AND MODE 6
(HIGH POWER AMPLIFIER UNIT OFF)

Quantity Compared	Mode 1	Mode 6
NOMINAL RADAR SETTINGS		
PRF, Hz	9581	3755
Pulse Width, μs	0.96	0.96
Scan Angle, deg	0±20	0±30
Range Alias	OFF	ON
Antenna Scan Rate, deg/s	37.5	14.625
Tape Speed, in/s	60	30
Transmitter Power	LOW	LOW
MEASURED TRANSMITTER POWER		
Transmitted Power, watts (flight #4)	150.5	171.0
Transmitted Power, watts (flight #6)	159.0	175.8

The transmitted power was measured both with the high power amplifier unit on and with it off before flight #9, which took place at Wallops Island. Table 3 below shows the calculated high power amplifier gain.

Table 3.-HIGH POWER AMPLIFIER GAIN

Transmitted Power Measured With High Power Amp. OFF	170 W
Transmitted Power Measured With High Power Amp. ON	1.90 kW
High Power Amplifier Gain	10.48 dB

Table 4 lists the flight-by-flight measured transmitted power and calculated receiver gain when R/T unit #1 was in use. Likewise, table 5 lists the same quantities resulting from the use of R/T unit #2. The results for the various modes are not tabulated individually; tables 4 and 5 represent averages for all the modes except mode 1. Pre- and post-flight, wide and narrow bandwidth results are given when applicable.

Table 4.-R/T #1 TRANSMITTED POWER AND RADAR GAIN FOR EACH FLIGHT (HIGH POWER AMPLIFIER UNIT OFF)

Flight Number	Pre-Flight			Post-Flight		
	Trans. Power, watts	Gain, dB Wide Bandwidth	Gain, dB Narrow Bandwidth	Trans. Power, watts	Gain, dB Wide Bandwidth	Gain, dB Narrow Bandwidth
#1, Peninsula	*	*	122.4	*	*	124.1
#2, Peninsula	*	*	123.9	*	124.9	*
#3, Philly	173	*	122.7	168	124.1	*
#4, Wallops	163	123.4	*	174	124.3	124.2
#5, Philly	178	124.3	123.3	176	124.7	123.6
#6, Norfolk	174	124.4	123.5	178	124.9	123.7
#7, Ches. Bay	170	124.9	123.8	173	124.5	123.4
#8, Wallops	178	*	*	*	*	*
#9, Wallops	170	*	121.7	165	*	121.4
Orlando #1	159	120.9	*	*	*	*
Orlando #2	154	123.0	121.8	154	122.6	121.4
Orlando #7	157	122.9	121.7	157	122.4	121.3
Orlando #8	169	123.0	121.8	*	*	*

Table 5.-R/T #2 TRANSMITTED POWER AND RADAR GAIN FOR EACH FLIGHT (HIGH POWER AMPLIFIER UNIT OFF)

Flight Number	Pre-Flight			Post-Flight		
	Trans. Power, watts	Gain, dB Wide Bandwidth	Gain, dB Narrow Bandwidth	Trans. Power, watts	Gain, dB Wide Bandwidth	Gain, dB Narrow Bandwidth
Orlando #3	197	123.6	122.5	185	122.8	121.7
Orlando #4	181	122.7	121.6	*	*	*
Orlando #5	189	123.3	122.1	*	*	*
Orlando #6	184	123.0	121.8	192	*	*
Orlando #9	195	123.3	122.1	*	*	*
Denver #1	192	123.0	121.8	*	*	*
Denver #2	202	123.3	122.2	*	*	*
Denver #3	193	123.0	121.9	*	*	*
Denver #4	186	122.8	*	*	*	*
Denver #5	196	123.2	122.2	*	*	*
Denver #6	203	*	*	*	*	*
Denver #7	195	123.4	122.3	185	122.8	121.8
Denver #8	189	123.4	122.4	*	*	*
Denver #9	199	123.4	122.4	*	*	*

* Data Not Available

Table 6 summarizes the average values for transmitted power, receiver gain, and receiver noise according to the R/T unit and the receiver bandwidth. The noise power was calculated for each combination of R/T unit and bandwidth, using the average gain value previously determined for that combination. Changes in transmitted power and gain from pre-flight to post-flight have been calculated where possible. However, the in-flight changes for R/T #2 were recorded for only two flights; therefore the results are averages of two values and are less significant than the corresponding numbers for R/T #1.

Table 6.-COMPARISON BETWEEN R/T #1 AND R/T #2, WIDE AND NARROW BANDWIDTHS SHOWING TRANSMITTED POWER, GAIN, AND NOISE AVERAGED OVER ALL FLIGHTS (HIGH POWER AMPLIFIER UNIT OFF)

Quantity Compared	R/T #1		R/T #2	
	Average Value	Change During Flight	Average Value	Change During Flight
Transmitted Power, W	168.0	+0.8	192.4	-4.7
Wide BW Gain, dB	123.8	+0.1	123.1	-0.7
Wide BW Noise, dBm	-108.5	####	-107.3	####
Narrow BW Gain, dB	122.9	+0.2	122.1	-0.6
Narrow BW Noise, dBm	-109.5	####	-108.3	####

Quantity Not Calculated

V. RESULT SUMMARY

A. Transmitted Power

Calibration data were recorded for 13 flights using R/T unit #1 and for 14 flights using R/T unit #2. Both units have a nominal transmitter power of 200 watts. From the calibration data, it was calculated that R/T #2 produced, on the average, 24.4 watts more power than did R/T #1. The individual average transmitted powers were 192.4 and 168.0 watts. The transmitted power for each R/T unit varied with time over a range of approximately 20 watts.

The transmitted power did not vary significantly with the radar mode except when mode 1 was used. On different days, the mode 1 transmitted power was measured at 20.5 watts and 16.8 watts less than the power for other modes. The main distinguishing characteristic of mode 1 is its higher pulse repetition frequency (PRF), which is 9581, compared to the other modes' PRF's of 4791 or less.

From the one available set of measurements, the high power amplifier unit was determined to have a gain of 10.48 dB, which was close to the nominal value of 10 dB.

B. Receiver Gain

The receiver gain for R/T #1 was about 0.8 dB higher than for R/T #2. When either R/T unit was in use, the wide bandwidth setting produced a receiver gain 0.9 to 1 dB higher than did the narrow bandwidth setting. The average receiver gains were 123.8 and 122.9 dB for R/T #1 at wide and narrow bandwidths, and 123.1 and 122.1 dB for R/T #2 at wide and narrow bandwidths.

The increase in gain with increased bandwidth is consistent with the difference in insertion loss measured for the particular bandpass filters employed in the I,Q chassis. It was determined by laboratory measurements that the 7 MHz filter had 3.39 dB insertion loss, while the 2 MHz filter had 4.26 dB insertion loss. The higher gain was calculated for the filter with the lower insertion loss.

With the exception of the first flight, the gain did not change more than one dB during any flight. Changes occurred equally often in either direction. Excluding Orlando flight #1, changes from one flight to another were 2.5 dB or less. It should be noted that the AGC attenuation is controlled by a computer which reads the voltage output from a logarithmic power detector (component LG in figure 3). If the output characteristic of the detector changes, the change in the resulting attenuator settings will cause the calculated gain to change, regardless of whether or not the receiver gain has actually changed.

C. Receiver Noise

The effective receiver system noise power seen at the receiver input was calculated for both R/T units. This noise power, in addition to antenna and radome noise, gives the total receiver noise. The noise power was calculated to be -108.5 dBm using R/T #1 and wide bandwidth, -109.5 dBm for R/T #1 and narrow bandwidth. The noise power was -107.3 dBm for R/T #2 and wide bandwidth, -108.3 for R/T #2 and narrow bandwidth. The noise power was, therefore, 1.2 dBm higher for R/T #2 than for R/T #1, and 1 dBm higher for the wider IF bandwidth than for the narrow IF bandwidth, regardless of the R/T unit.

D. Gain and Noise Power Calculation Check

Appendix C explains, with an example, how the gain and noise calculations were checked, using data from a range of IFR input levels. In the example shown, the gains agreed within 1.3 dB, indicating that the method of calculation was satisfactory.

REFERENCES

1. IFR Inc., "Operation Manual: RDX/RDC-7708 Weather Radar Test Set," Appendix A: "Specifications," Wichita, Kansas, 1986, pp. A-1 through A-5

2. Research Triangle Institute, "Summary Description and Operating Characteristics of the Windshear Experimental Radar Data System, Interim Report," RTI/4500/002-02I, Research Triangle Park, North Carolina, January 1991

Appendix A: 1991 WINDSHEAR RADAR EXPERIMENT FLIGHTS

Flight Name	Date	R/T Unit
#1, Peninsula	2-15-91	1
#2, Peninsula	2-22-91	1
#3, Philadelphia	2-28-91	1
#4, Wallops Island	3-15-91	1
#5, Philadelphia	3-20-91	1
#6, Norfolk	3-26-91	1
#7, Chesapeake Bay	3-28-91	1
#8, Wallops Island	5-17-91	1
#9, Wallops Island	5-23-91	1
Orlando #1	6-09-91	1
Orlando #2	6-10-91	1
Orlando #3	6-13-91	2
Orlando #4	6-15-91	2
Orlando #5	6-16-91	2
Orlando #6	6-17-91	2
Orlando #7	6-18-91	1
Orlando #8	6-19-91	1
Orlando #9	6-20-91	2
Denver #1	7-07-91	2
Denver #2	7-08-91	2
Denver #3	7-09-91	2
Denver #4	7-10-91	2
Denver #5	7-11-91	2
Denver #6	7-13-91	2
Denver #7	7-17-91	2
Denver #8	7-18-91	2
Denver #9	7-20-91	2

Appendix B: EXPERIMENTAL WINDSHEAR RADAR MODES [2]

Radar Parameter	Mode Number 1	2	3	4	6	8	13	19
PRF, Hz	9581	4791	3755	2395	3755	3755	3755	3755
Pulse Width, μs	0.96	0.96	1.92	3.84	0.96	1.92	0.96	0.96
Display Mode[1]	WX	WX	WX	WX	MAP	MAP	MAP	MAP
Display Gain, dB	32	32	32	32	32	32	32	32
Display Range, nmi	5	10	15	30	15	15	15	15
Antenna Polarization	HOR	HOR	HOR	HOR	HOR	HOR	HOR	HOR
Scan Angle, deg	0±20	0±20	0±30	0±45	0±30	0±30	0±30	0±0
Tilt Angle, deg[2]	0	0	0	0	-3	-3	A20000	0
Window Delay Time, μs	5.76	5.76	7.68	11.52	5.76	7.68	5.76	5.76
Range Sampling[3]	0	1	0	0	0	0	0	0
Range Alias[4]	OFF	OFF	OFF	OFF	ON	ON	ON	ON
Tape Speed, in/s	60	30	30	30	30	30	30	30
Ant.Scan Rate, deg/s	37.5	18.75	14.625	12.5	14.625	29.25	14.625	14.625
Number of Range Bins	69	69	91	98	91	91	91	100
Range Resolution, ft	472.1	472.1	944.2	1888.4	472.1	944.2	472.1	472.1
Sampling Interval, ft	472.1	944.2	944.2	1888.4	472.1	944.2	472.1	472.1
Window Delay Range, ft	2833	2833	3777	5665	2833	3777	2833	2833
Window Length, nmi	5.36	10.72	14.14	30.46	7.07	14.14	7.07	7.77
Alias Windspeed, kn	150.1	75.1	58.8	37.5	58.8	58.8	58.8	58.8
Antenna Scan Mode	AZ	AZ	AZ	AZ	AZ	AZ	AZ	AZ
Antenna Scan Time, s	1.1	2.1	4.1	7.2	4.1	2.1	4.1	4.1
Avail. Run Time, min	30	60	60	60	60	60	60	60

Definitions

[1] WX and MAP refer to standard Collins display modes for looking at the weather or at the ground. The displays show reflectivity, rather than Doppler, information.

[2] Tilt Angle = A20000: A mode used only when the aircraft is descending; tilt angle changes automatically to keep the antenna beam's intersection with the ground at a fixed distance of 20,000 ft in front of the aircraft.

[3] Range Sampling: Number of range bins skipped between recorded bins

[4] Range Aliasing { OFF: PRF is constant for entire transmitted frame.
ON: PRF is halved after 96th pulse in each transmitted frame.

Appendix C: GAIN AND NOISE CALCULATION CHECK

Receiver gain has been calculated using test signal inputs at -50 dBm, which is much higher than the system noise level. Receiver noise has been calculated using the average calculated gain when the test signal inputs were -127 dBm, which is 70 times lower than the noise level. As a check for the gain and noise calculations, gain was recalculated by putting an average noise power back into equation 1 together with data recorded from a range of signal inputs between -127 dBm and -50 dBm. Data collected within a few minutes were used to calculate a series of gains. If the noise powers were correct, the resulting gains should all be the same.

The following example is from the post-flight #4 calibration data set. This calibration was done using R/T #1 and the wide IF bandwidth. The average calculated noise power for the data set was

NOISE POWER = 1.444 E-11 mW = -108.4 dBm

$$\text{GAIN} = \frac{(\text{I,Q POWER})\ (\text{AGC})}{(\text{IFR POWER}) + (\text{NOISE POWER})}$$

$$\text{at IFR} = -127\ \text{dBm: GAIN} = \frac{(6.353\ \text{mW})5.534}{1.995\ \text{E-13 mW} + 1.444\ \text{E-11 mW}} = 123.8\ \text{dB}$$

$$\text{at IFR} = -115\ \text{dBm: GAIN} = \frac{(7.762\ \text{mW})5.888}{3.162\ \text{E-12 mW} + 1.444\ \text{E-11 mW}} = 124.1\ \text{dB}$$

$$\text{at IFR} = -105\ \text{dBm: GAIN} = \frac{(14.69\ \text{mW})9.550}{3.162\ \text{E-11 mW} + 1.444\ \text{E-11 mW}} = 124.8\ \text{dB}$$

$$\text{at IFR} = -90\ \text{dBm: GAIN} = \frac{(20.46\ \text{mW})1.614\ \text{E2}}{1.000\ \text{E-9 mW} + 1.444\ \text{E-11 mW}} = 125.1\ \text{dB}$$

$$\text{at IFR} = -70\ \text{dBm: GAIN} = \frac{(23.01\ \text{mW})1.259\ \text{E4}}{1.000\ \text{E-7 mW} + 1.444\ \text{E-11 mW}} = 124.6\ \text{dB}$$

$$\text{at IFR} = -50\ \text{dBm: GAIN} = \frac{(21.63\ \text{mW})1.233\ \text{E6}}{1.000\ \text{E-5 mW} + 1.444\ \text{E-11 mW}} = 124.3\ \text{dB}$$

Since the calculated gain varies by only 1.3 dB over all of the S/N ratios, the noise power -108.4 dB is approximately correct for this data set.

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13. ABSTRACT *(Maximum 200 words)*

An experimental windshear Doppler radar was flown on 27 occasions during a series of flight experiments in 1991. Radar calibrations were performed by the flight team to monitor the transmitter power and receiver gain from pre-flight to post-flight and from one day to another. From the recorded calibration data, the receiver gain and effective receiver system noise have been calculated and tabulated, together with the transmitter power. These quantities of interest are compared for two receiver/transmitter (R/T) units and two intermediate frequency (IF) bandwidths that were tested in various modes. It was found that, in most operating modes, gain stayed within a 2.5-dB range and transmitter power stayed within a 20-watt range. R/T #1 had 0.8 dB more gain and 1.2 dBm less noise power than R/T #2. The 7-MHz IF bandwidth resulted in 1 dB more gain and 1 dBm less noise than the 2-MHz IF bandwidth. Depending on the R/T unit and IF bandwidth, the effective system noise power averaged between -107.3 dBm and -109.5 dBm.

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