NOAA Technical Memorandum ERL ARL-66

DEPARTMENT OF COMMERCE ★ UNITED STATES OF AMERICA ★

A FEASIBILITY STUDY FOR THE APPLICATION OF K-BAND RADAR IN THE INVESTIGATION OF COOLING TOWER PLUMES

Norman R. Ricks

Air Resources Laboratory
Idaho Falls, Idaho
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noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

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A FEASIBILITY STUDY FOR THE APPLICATION OF K-BAND RADAR IN THE INVESTIGATION OF COOLING TOWER PLUMES

N. R. Ricks

The feasibility of using commercially available K-band (1 cm) radar for indirect sensing of cooling tower plumes is investigated. Using the radar equation, commercially available systems are evaluated by means of a computer model which estimates the strength of the expected return signal under sampled conditions known to exist in actual plumes. Recommendations are made for the adaptation of available radar systems and for areas of additional study. Complete data and program documentation are provided.

1. INTRODUCTION

As larger and more power plants are built, it becomes increasingly important that we understand the physics of their cooling tower plumes. Several examples point out this need. Satellite imagery has revealed continuous cloud streets hundreds of miles long resulting from waste heat or seeding agents released into a conditionally unstable atmosphere (Hosler, 1977). Deposition and possible pollution of the ground have been measured in areas where cooling tower plumes are frequently embedded in stratus clouds (Overcamp, et al 1976). Augmented snowfall downwind of a power plant has been observed to be, in fact, cooling tower plume precipitation (Huff, 1972; Agee, 1971). Basic questions have been raised regarding the effects of effluent gasses within the visible plume, the effects of unique cloud drop distributions, and so on (Hanna and Gifford, 1975).

At the present time, research which may lead to an understanding of some of these questions is limited in areal coverage and amount. In situ measurements such as those made by aircraft penetrations are costly, and are limited in number (Thomson, et al 1976). Our understanding of the freezing process within plumes of this type is limited, and is based primarily upon laboratory, not field measurements (Fukuta, 1958). Likewise, the behavior of plume droplets in the presence of gaseous pollution and dissolved salts is a matter of continuing research (Hanna and Gifford, 1975).

It would be helpful to obtain quantitative data--in real time if possible--over a wide range of plume conditions, all at a reasonable cost (Carson, 1976). Remote sensing technology may provide such a cost effective means of data acquisition. Years of steady progress in cloud physics applications have laid a theoretical basis for obtaining many of the parameters of interest. By means of variable frequency systems, plume droplet distributions may be sensed at various ranges downwind. From this information, an understanding of the droplet growth physics may be inferred. The varying attenuation coefficients of waste gasses within the plume may provide a means to identify them. Changes in the polarization of the signal might be used as a means to study the freezing process within the plume. In addition, remote sensing is capable of inferring more representative mean values and greater volumetric coverage than is possible with more conventional systems. Finally, in many cases, the measurements may be taken outside the plant area, allowing an added degree of safety and versatility.

In order to establish the feasibility of using a particular remote sensing system, several questions need to be answered. What parameters might be measured? What off-the-shelf equipment is available as a starting point? What are minimum performance characteristics which may be required? How does the available hardware compare? What changes need to be made?

This paper investigates the foregoing questions and examines the feasibility of using, in particular, K-Band radar to study the behavior of cooling tower plumes. The theory of remote sensing is applied to the problems at hand, and on this basis the basic specifications required of the hardware are developed. This section is followed by a description of the commercially available systems meeting the criteria. Basic input data characteristic of the plumes and of the sensing systems is documented. Sample calculations are used to show how this data is combined with the theory to yield a precise estimate of the system performance under various conditions. A formal presentation of the computer program (Appendix III) documents the details. The results of the feasibility study are then presented. System strengths and weaknesses are evaluated and improvements are suggested. Some simple modifications are tested. Finally, recommendations for the direction of further research and suggested approaches to modifying the equipment form the concluding section.

2. PRELIMINARY SPECIFICATIONS

This paper addresses the particular problem of obtaining a detectable returned signal which may be easily and economically analyzed to provide data on the plume density profile, its liquid water content, drop size distribution, the freezing process, and information on the effect of non-aqueous waste gasses within the plume.

These study goals presuppose that a detectable signal is scattered from the plume and returned to the sensor, and that the beam characteristics allow various sections of the plume to be defined and examined.

Current indirect sensing technology makes use of wave-media interactions of several types. Electromagnetic radiation is used in various radar and lidar systems; acoustic energy is used in sodar. One can evaluate the relative strengths and weaknesses of radar, lidar and sodar on the basis of information such as that compiled by Little (1972, 1973). Sodar is severely range limited, and has poor beam dimensional characteristics. The interaction of the acoustic wave with the plume droplets and aerosol is extremely weak, and no polarization data is obtainable. Lidar systems have a definite research potential, and are especially useful in their ability to infer plume density profiles (Uthe and Johnson, 1976), drop distributions (Cohen, 1972), and potentially (by means of Raman backscatter) to obtain information on gaseous pollutants. Low pulse repetition frequencies and, relatively speaking, immature data analysis technology make lidar systems a more difficult and less economical alternative at this time.

K-band (1 cm) radar has several promising characteristics. Because the wavelength is so much larger than the cloud droplets it interacts with, Rayleigh backscattering, with its characteristically large backscattered intensity, dominates. Polarization information may be obtained from the beam by means of specialized hardware configurations. Narrow beams and short pulse lengths sufficient to define the plume are obtainable. Attenuation characteristics are acceptable, and data analysis and display techniques are well advanced and comparatively easily accessed and adapted. Additional system comparisons are made in table 1.

Table 1

System Performance	Sodar	Lidar	K-band Radar	Other (Longer λ) Radar
Beam dimenstions	Poor	Very good	Good	Fair
Pulse length	Good	Very good	Good*	Good*
Hydrometeor scatter coefficient	Poor	Fair	Good	Poor
Polarization data	N/A**	Difficult	Available	Available
Lack of attenuation	Poor	Poor	Good	Very good
Steerable beam, low angle	Poor	Easy	Easy	Easy
DATA				
Density Profile	0	x	x	0
Liq. H_2O content	0	?	?	0
Drop Distri.	0	x	?x	0
Freezing Process	0	?	x	?x
Waste Gasses	0	x	?x	0
Data display and analysis ease	Good	Poor	Good	Good

*range dependent
**Sodar not polarized

Before sophisticated parameters involving signal polarization and unique scattering and attenuation characteristics may be examined, it is first necessary to obtain a detectable signal from accurately defined portions of the plume. The derivation of the radar equation used in the following analysis is given by Battan (1973). The form applicable to Rayleigh scattering is:

$$P_{R_o} = \frac{P_T\, G^2\, \lambda^2\, \theta\, \phi\, h}{512 * 2 \ln 2 * r^2\, \pi^2} \sum_{\mathrm{vol}} \sigma_i$$

where

P_{R_o} = returned power (before attenuation calculations)

P_T = transmitted power

G = antenna gain over isotropic

λ = radar wavelength

θ = beam width

ϕ = beam height

h = pulse length

r = range to target

$\Sigma\sigma_i$ = radar reflectivity, summed backscattering cross-sections of targets per unit volume.

Battan (1973) points out the limiting angular resolution of θ, the beam width, and the limiting range resolution of one-half the pulse length.

The preliminary limiting specifications become, then, a short wavelength radar system of small beam dimensions and short pulse length, but of adequate sensitivity to detect the heavily attenuated returning signal.

3. COMMERCIALLY AVAILABLE SYSTEMS

Because attenuation limits any application involving long ranges or deep clouds, the 1-cm radar has never enjoyed a wide popularity in storm detection or fire control systems. In recent years, the only operational K band radar was used as a fixed beam, vertically directed celiometer. This was the AN/TPQ-11[1] radar, built by Olympic Radio and Telephone Company and Lear Siegler Corporation.

The TPQ-11 is an extremely sensitive radar, primarily because of its high gain antenna and low internal system noise characteristics. Approximately 45 units were originally produced. By 1972, high

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[1] Decode sheet for military equipment designators is given in Appendix A.

Table 2. Radar Parameters Compared

TPQ-11 (Boyajian, 1976)	APQ-148-4	APQ-148-3	APQ-148-2	APQ-148-1	RC5-4	RC5-3	RC5-2	RC5-1	
34.5-35.6	16-17	16-17	16-17	16-17	16-17	16-17	16-17	16-17	ν (GH$_z$)
.87-.84	1.87-1.76	←					→	1.87-1.76	λ (cm)
1.0	3.0	1.2	0.4	0.2	3.5	1.7	0.5	0.2	τ (μsec)
300	900	360	120	60	1050	510	150	60	h (m)
500	300	800	2400	2400	266	1064	2128	2128	PRF (sec^{-1})
300	500	187.5	62.5	62.5	564	141	70.5	70.5	γ_{max} (km)
.004	.02	.02	.02	.02	.012	.012	.012	.012	θ (rad)
.004	.03	.03	.03	.03	.025	.025	.025	.025	ϕ (rad)
25	60	←					→	60	P_T (KW)
119526	1585	←	→	1585	3162	←	→	3162	G
-100	-105	-102	-100	-98	-105	-102	-100	-98	P_{MIN} (dBm)

maintenance costs - primarily replacement magnetrons at $8000 each - were forcing many into surplus. At the present time this process is almost complete. Some sets are now available in surplus salvage areas, and four more or less recognizable sets are located at the National Center for Atmospheric Research in Boulder, Colorado. Performance characteristics and parameters from the radar equation are listed in table 2.

K band radar technology received its most recent boost when the Defense Department negotiated a contract with NORDEN, a division of United Technologies Corporation in Norwalk, Connecticut for the production of two separate airborne K band sets - one for use in the Lockheed C5A Galaxy, the other to be used in the Grumman A6 Intruder.

As table 2 indicates, there are certain similarities to each of the Norden sets (Levitan, 1977). The wavelengths are comparable - in the K_u band at approximately 1.8 cm. The peak transmitter power of 60 kW, the antenna gain of approximately 32 dB, and the versatility of four separate operating modes spanning a range of pulse lengths and pulse repetition frequencies are other similarities. Although the exact beam dimensions differ, both of the Norden radars employ a "cosecant squared" type antenna. In contrast to the parabolic dish of the TPQ-11, these antennas are designed to optimize both the transmitted and received wavetrain in such a way that there is a constant "illumination" intensity across the beam, irrespective of range (Jung, 1977). Because this type of antenna design requires it, and because airborne systems require more exact azimuthal resolution, the beam from the cosecant squared antennas is narrowed from side to side, and elongated in the vertical.

The C5A radar, designated "RC5" in this report, has two separate antenna systems which allow a selection of either X (3 cm) or K_u (1.8 cm) wavelengths. These antennas are shown in figure 1.

Although production for each of the Norden radars has been completed, the firm recently announced a contract to begin substantial updating and maintenance of the approximately 70 RC5 systems in operational use.

The second Norden radar, designed for the A6, is the AN/APQ-148. Its major subsystems are shown in figure 2. Certain changes in the display components necessitated by rearrangements of the aircraft cockpit resulted in the issuance of a second designator to describe these cosmetic changes. The changed version of the APQ 148 is the AN/APQ-156.

Comparison of each of the three primary radar systems discussed in this report may be made in table 2. The various pulse lengths and pulse repetition frequencies characterize each of the modes of the Norden systems, and are selected by the radar operator from the control panel.

4. INPUT DATA DOCUMENTATION

The calculations made in this feasibility study make use of sampled data which characterizes both the cooling tower plume and the performance of the radar signal in such an environment.

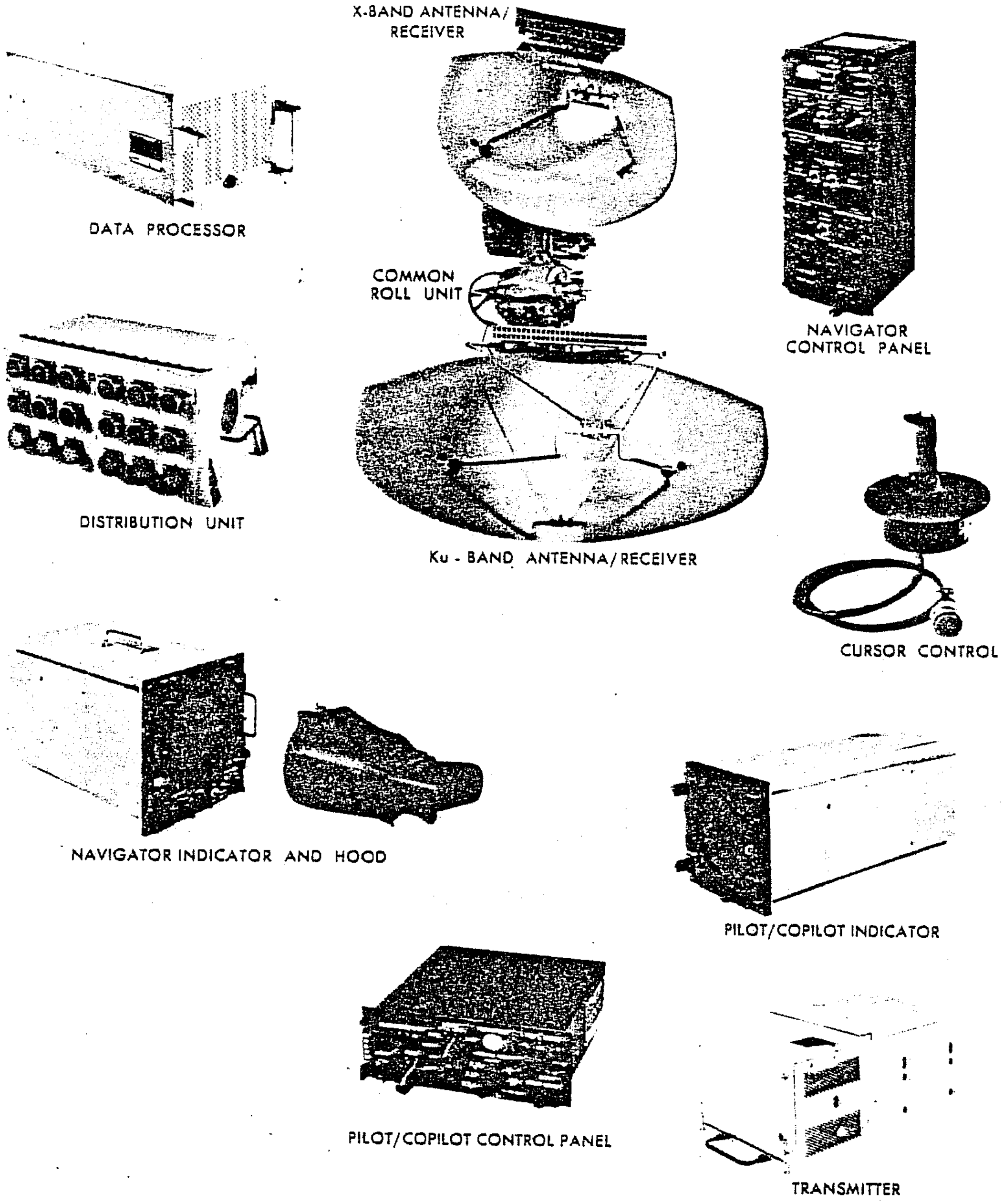

Figure 1. Basic subsystems of RC5 radar system. Photo courtesy NORDEN Division, United Technologies Corporation.

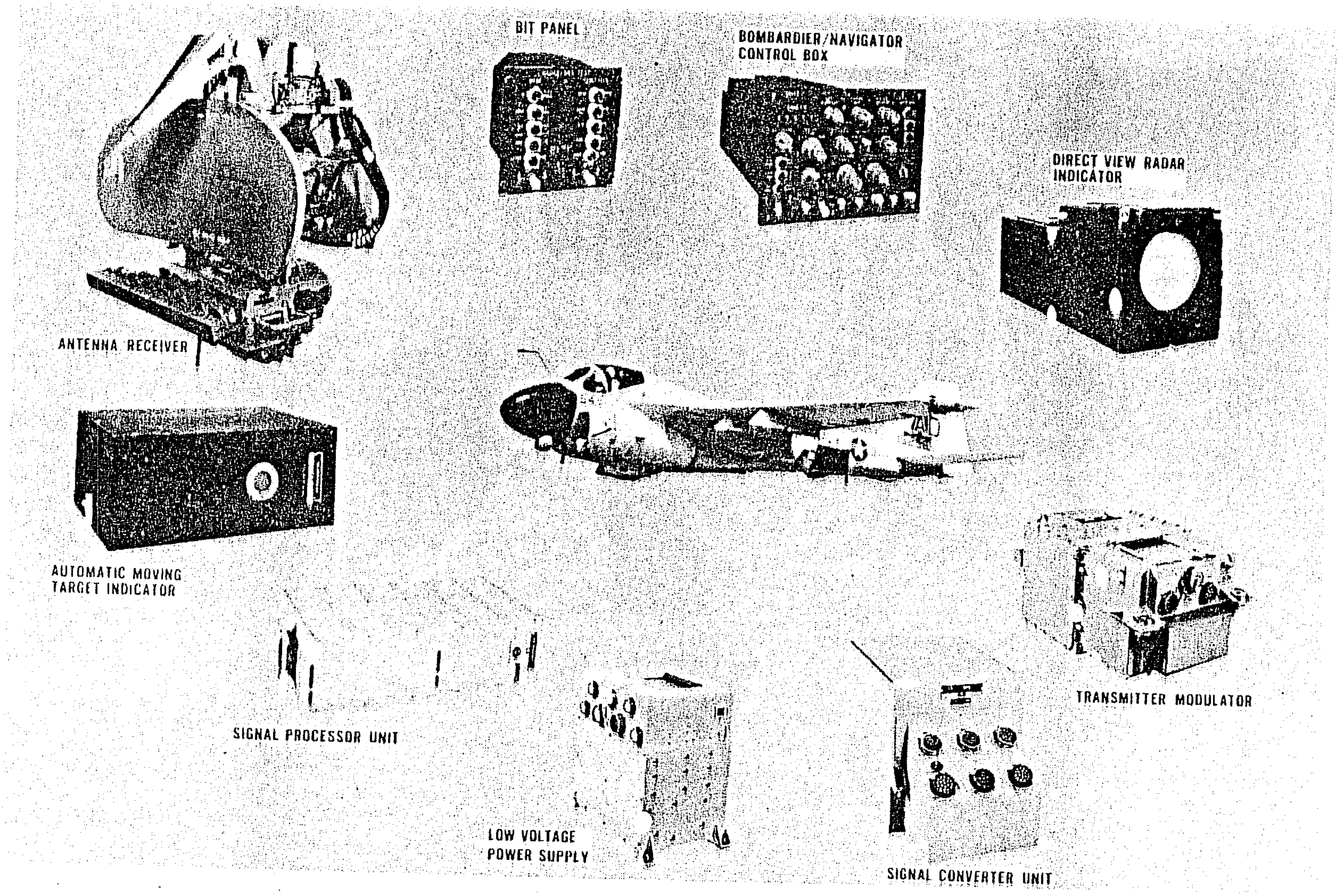

Figure 2. Basic subsystems of AN/APQ-148 (156) radar system. Photo courtesy NORDEN Division, United Technologies Corporation.

The plume data consist of sampled drop distributions, and both ambient and within-plume state parameters, obtained by aircraft penetration of the Keystone (Pennsylvania) power plant plume by the Penn State Aero-Commander (Pena, 1977). The data was obtained in 1976 and is listed in table 3.

Radar signal performance data, notably the dielectric constant of water, which is used for both the scattering calculations, and the attenuation (absorption) term, were obtained from the sources indicated in table 4. The tabulated values of the imaginary part of minus K and the squared absolute value of K were taken from Gunn and East as cited by Battan (1973). Because of the abnormally high plume temperatures these data were extended beyond the limits of their tables by means of the formula of Grant, et al (1957) as cited by Westwater (1972).

Radar performance data was obtained from the files of the National Center for Atmospheric Research (for the AN/TPQ-11) and from the advanced concepts development section at Norden.

5. SAMPLE CALCULATIONS

Predicting the strength of the returning radar signal requires the following minimum data.

For the plume:

- The cloud drop distribution in terms of numbers of droplets per unit volume whose diameters lie within a specified size range.
- The values of the state parameters (temperature, pressure, density) applicable to the plume and surrounding environment.

For the radar:

The radar system parameters from the radar equation, including

- The peak transmitted power, P_T
- The antenna gain, G
- The beam width, θ
- The beam height, ϕ
- The pulse length, τ (time) or h (length)
- The wavelength, λ

Using the Keystone #1 drop distribution as an example, the back-scattering cross-section for Rayleigh scattering may be obtained as follows:

Table 3. Sampled Plume Data

Droplet Diameter (Microns)	1	2	3	4	5	6	7
1							
2	69	164	666	183			
3							
4							
5	363	366	732	289	27	56	36
6							
7							
8	374	486	659	361	90	86	72
9							
10	466	427	792	897	123	115	96
11							
12							
13	95	295	390	370	104	120	107
14							
15	8	143	216	99	23	66	25
16							
17							
18		21	33	47	2	17	2
19							
20			18			12	2
Plume Temp(°C)	20	20	20	20	20	20	20
Air Temp(°C)	5.8	5.8	5.8	5.8	16.6	16.6	16.6
Pressure (mb)	990	990	990	990	990	990	990
Water Vapor Density(gm^{-3})	4.06	4.06	4.06	4.06	8.3	8.3	8.3

Table 4. Temperature Dependent Radar Parameters

ε = complex dielectric constant
m: complex index of refraction
n: ordinary index of refraction
i: $\sqrt{-1}$
k: absorption coefficient

$$m = n - ik, \quad \varepsilon = m^2$$

$$\frac{m^2-1}{m^2+2} = \frac{\varepsilon-1}{\varepsilon+2} = K.$$

The Components of the Complex Index of Refraction, $|K|^2$, and the Imaginary Part of $(-K)$ of Water as Functions of Temperature and Wavelength

Quantity	Temperature (°C)	Wavelength (Cm)			
		10	3.21	1.24	0.62
n	20	8.88	8.14	6.15	4.44
	10	9.02	7.80	5.45	3.94
	0	8.99	7.14	4.75	3.45
	− 8	....	6.48	4.15	3.10
κ	20	0.63	2.00	2.86	2.59
	10	0.90	2.44	2.90	2.37
	0	1.47	2.89	2.77	2.04
	− 8	....	....	2.55	1.77
$\lvert K\rvert^2$	20	0.928	0.9275	0.9193	0.8926
	10	0.9313	0.9282	0.9152	0.8726
	0	0.9340	0.9300	0.9055	0.8312
	− 8	....	....	0.8902	0.7921
Im$(-K)$ ...	20	0.00474	0.01883	0.0471	0.0915
	10	0.00688	0.0247	0.0615	0.1142
	0	0.01102	0.0335	0.0807	0.1441
	− 8	....	....	0.1036	0.1713

SOURCE: Gunn and East 1954.

from Battan (1973)

for extrapolation:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_o \quad \varepsilon_\infty}{1+\left(\frac{i\lambda_s}{\lambda}\right)^{1-\gamma}}$$

where $\varepsilon_\infty = 4.5 \quad \gamma = .02$

$$\varepsilon_o = \frac{32155.45}{T(K^\circ)} - 29.62$$

$$\log_{10} \lambda_s = \frac{921.0935}{T(^\circ K)} - 2.9014$$

from Westwater (1972)

	Droplet diameter (microns)	2	5	8	10	13	15
Given:	Number droplets per CM^3	69	363	374	466	95	8

$T = 20^\circ C$, $P = 990$ mb, water vapor density = $4.06\ g\ m^{-3}$

and the formula for the backscattering cross-section for a single particle,

$$\sigma_i = \frac{\pi^5}{\lambda^4} |K|^2 D_i^6$$

using Table 4 and $\lambda = 1.87$ cm

$$\sigma_{2\mu} = .13788\text{-}20^{*}\ cm^2$$

$$\sigma_{5\mu} = .33663\text{-}18\ cm^2$$

$$\sigma_{8\mu} = .56477\text{-}17\ cm^2$$

$$\sigma 10\mu = .21544\text{-}16\ cm^2$$

$$\sigma 13\mu = .10399\text{-}15\ cm^2$$

$$\sigma_{15\mu} = .24540\text{-}15\ cm^2$$

The backscattering cross-section for a single particle is multiplied by the number of particles of that size per unit volume (for 2μ diameter drops:)

$$2\mu: \quad .13788 \times 10^{-20} \times 69 \text{ drops} = .95140 \times 10^{-19}\ cm^2$$

and these totals are summed for all particle sizes per unit volume

$$\eta = \sum_{vol} \sigma_i = .24117 \times 10^{-13}\ cm^{-1}.$$

The next goal for the calculations is to derive P_{R_0}, a value for the power (P)scattered back to the receiving antenna (R) when attenuation is not considered (o). The radar equation's exact form, assuming Rayleigh scattering, is (Batten, 1973)

$$P_{R_0} = \frac{P_T\, G^2 \lambda^2 \theta \phi h}{512*2\ln 2*r^2 \pi^2} \sum_{vol} \sigma_i$$

For the RC5 mode 1 typical values are

$P_T = 60$ Kw

$G = 3162$

$\lambda = 1.87$ cm

$\theta = .012$ radians

$\phi = .025$ radians

$h = 60$ meters

---

* where "-20" denotes 10^{-20}

In this example, let us consider a range of 1.2 km. Using the results calculated for the keystone #1 drop distribution,

$$\sum_{vol} \sigma_i = .24117*10^{-13}\ cm^{-1} \text{ (from table 6)}$$

so combining these factors, making the length units consistent, and scaling so P_{R_0} is in watts, the equation becomes

$$P_{R_0}\ (\text{watts}) = \frac{P_T(KW)*G^2*\lambda^{2}\text{-}(cm^2)*\theta*\phi*h(m)}{512*2\ln 2*\pi^2*r^2(km^2)} * \sum_{vol} \sigma_i(cm^{-1})$$

$$\doteq \frac{60*(3162)^2*(1.87)^2*.012*.025*60}{512*1.386*9.870*(1.2)^2} *.24117 \times 10^{-13}$$

and scaling for dimensional uniformity,

$$= P_{R_0} * \frac{10^3 W}{KW} * \frac{10^2\ cm}{m} * \frac{km^2}{10^{10}\ cm^2}$$

$$= P_{R_0} * 10^{-5}$$

$$P_{R_0} = .90290 \times 10^{-15} \text{ watts}$$

The attenuation calculations make use of the following formulus taken from Van Vleck as cited by Bean, et al, (1969).

" The oxygen absorption at T = 293°K and standard atmospheric pressure in decibels per kilometer, $\gamma 1$, is given by the expression

$$\gamma 1 = \frac{0.34}{\lambda^2}\left[\frac{\Delta\nu_1}{1/\lambda^2 + \Delta\nu_1^{\ 2}} + \frac{\Delta\nu_2}{(2+1/\lambda)^2 + \Delta\nu_2^{\ 2}} + \frac{\Delta\nu_2}{(2-1/\lambda)^2 + \Delta\nu_2^{\ 2}}\right]$$

where λ is the wavelength for which the absorption is to be determined and $\Delta\nu_1$ and $\Delta\nu_2$ are line-width factors with dimensions of reciprocal centimeters.

" The water-vapor absorption at 293°K arising from the 1.35-cm line, 2, is given by

$$\frac{\gamma 2}{\rho} = \frac{3.5 \times 10^{-3}}{\lambda^2}\left[\frac{\Delta\nu_3}{(1/\lambda-1/1.35)^2 + \Delta\nu_3^{\ 2}} + \frac{\Delta\nu_3}{(1/\lambda+1/1.35)^2 + \Delta\nu_3^{\ 2}}\right]$$

where ρ is the absolute humidity and $\Delta\nu_3$ is the line-width factor of the 1.35-cm water-vapor absorption line. The additional absorption arising from absorption bands above the 1.35-cm line, γ_3, is described by

$$\frac{\gamma 3}{\rho} = \frac{0.05\Delta\nu 4}{\lambda 2}$$

where $\Delta\gamma 4$ is the effective line width of the absorption bands above the 1.35-cm line."

The effective line widths and corrections for non-standard conditions are given below (from Bean, et al 1969).

Line width	Temperature, °K	Value, $cm^{-1}\ atm^{-1}$
$\Delta\nu 1$	293	0.018
$\Delta\nu 2$	300	0.049
$\Delta\nu 3$	318	0.087
$\Delta\nu 4$	318	0.087

Absorption, db/km	Multiplying factor	Line width, cm^{-1}
$\gamma 1$	$\frac{0.34}{\lambda 2}\ \frac{P}{1013.25}\left(\frac{293}{T}\right)^2$	$\Delta\nu 1\frac{P}{1013.25}\left(\frac{293}{T}\right)^{3/4}$ and $\Delta\nu 2\frac{P}{1013.25}\left(\frac{300}{T}\right)^{3/4}$
$\frac{\gamma 2}{\rho}$ *	$\frac{0.0318}{\lambda^2}\left(\frac{293}{T}\right)^{5/2} e^{-644/T}$	$\Delta\nu 3\frac{P}{1013.25}\left(\frac{318}{T}\right)^{1/2}(1+0.0046\rho)$
$\frac{\gamma 3}{\rho}$ *	$\frac{0.05}{\lambda 2}\left(\frac{293}{T}\right)$	$\Delta\nu 4\frac{P}{1013.25}\left(\frac{318}{T}\right)^{1/2}(1+0.0046\rho)$

---

* ρ is water-vapor density in grams per cubic meter.

Using the state parameters given for the keystone #1 distribution, i.e.,

Atmospheric $T = 5.8°C$
$P = 990$ mb
water vapor $\rho = 4.06\ gm^{-3}$

these formulas reduce to

γ_1 (oxygen absorption) = $.99687 \times 10^{-2}$ dB/Km
γ_2 (water vapor absorption) = $.77442 \times 10^{-2}$ dB/Km
γ_3 (additional absorption) = $.56371 \times 10^{-2}$ dB/Km

where K gas = $\gamma_1 + \gamma_2 + \gamma_3$

and allow the calculation of the attenuated received power P_R from its unattenuated counterpart P_{R_O} as follows:

$$P_R = P_{R_O} * 10^{\{-.2*K_{gas}* r\}}$$

where K_{gas} is gas attenuation in dB/km and r is range to target.

The program calculates attenuation from intervening clouds if such are present. This option is not used in the sample calculation. This attenuated power value in watts may be converted to decibel form and expressed in standard decibels below a milliwatt, dBM, by means of

$$P_R(\text{dBM}) = 10 \log_{10} \frac{P_R}{.001}$$

This result, the attenuated received power expressed in dBM, then may be calculated for each range of interest and compared to the minimum threshold of detectability for each radar set. The computer program makes these calculations for each radar, range, and drop distribution, and plots the results graphically for easier comparison.

6. RESULTS

The results of the calculations of expected received power after attenuation are given in figures 3 through 9. Each figure displays attenuated received power in dBm versus range in kilometers for one given drop distribution. The relative performance of each of the radar systems for a given drop distribution remains constant (the system characteristics remain unchanged) although the absolute value of the return varies as drop distributions change.

The radars relative performance is clearly traceable to their internal system characteristics. The top performing TPQ 11 has the advantages of high antenna gain, narrow beam dimensions and relatively high power. Both the RC5 and the APQ148 systems show progressively better returned signal strength as the operating modes are increased from one through four, corresponding with the increasing pulse length. The APQ148 system lags the RC5 in each case, due to its slightly lower antenna gain and wider beam dimensions. The 99.2 system, an imaginary hybrid having the pulse length and power of the RC5.1 and the beam dimensions and antenna gain of the TPQ-11, is the first runner-up in performance, indicating the desirability of improving the antenna of a modern system.

Several conclusions are apparent.

The "visibility" of a plume to the radar is strongly dependent upon the drop distribution of the plume. It is interesting to note the

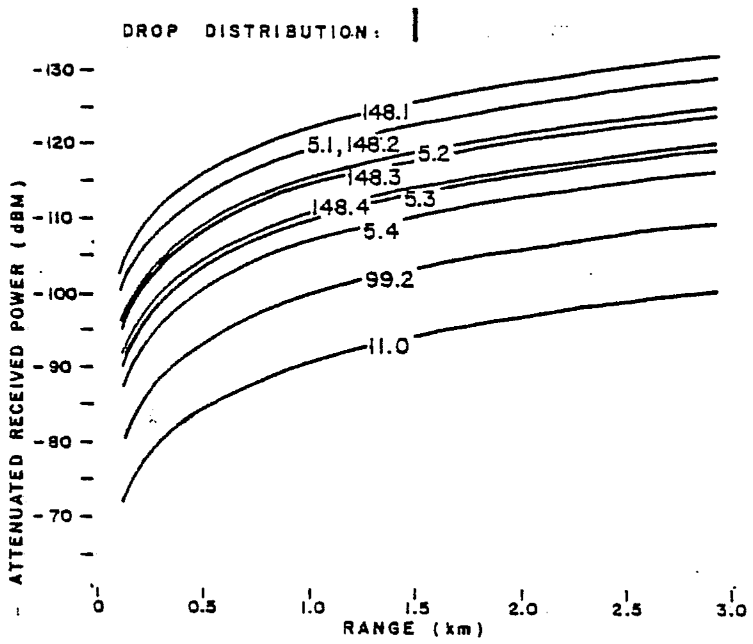

Figure 3.

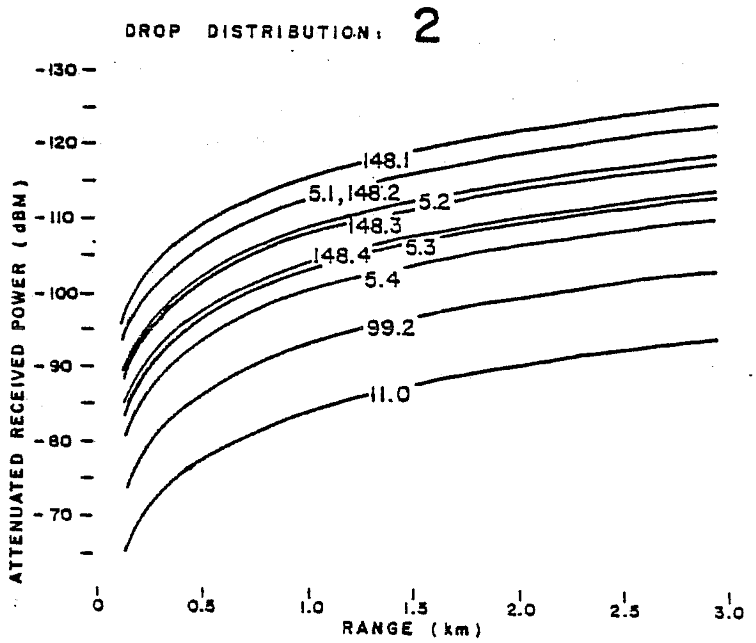

Figure 4.

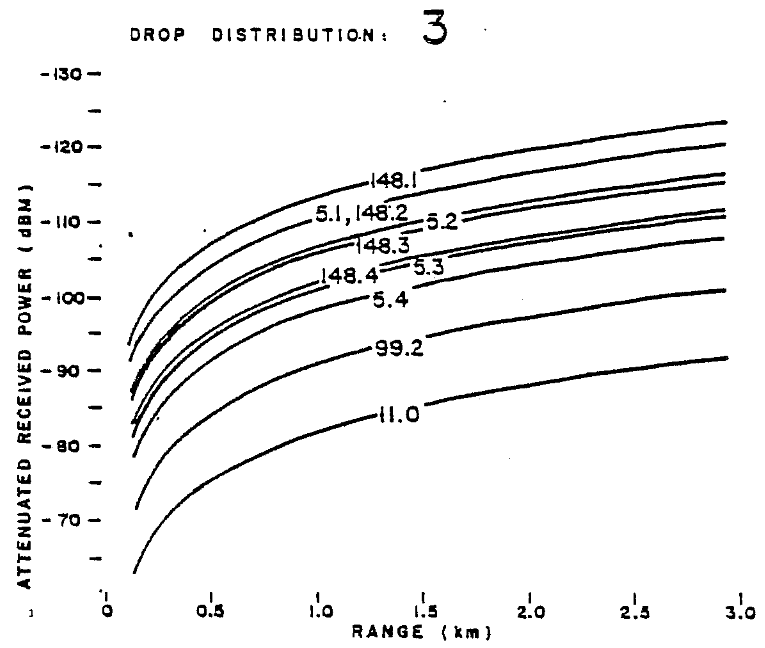

Figure 5.

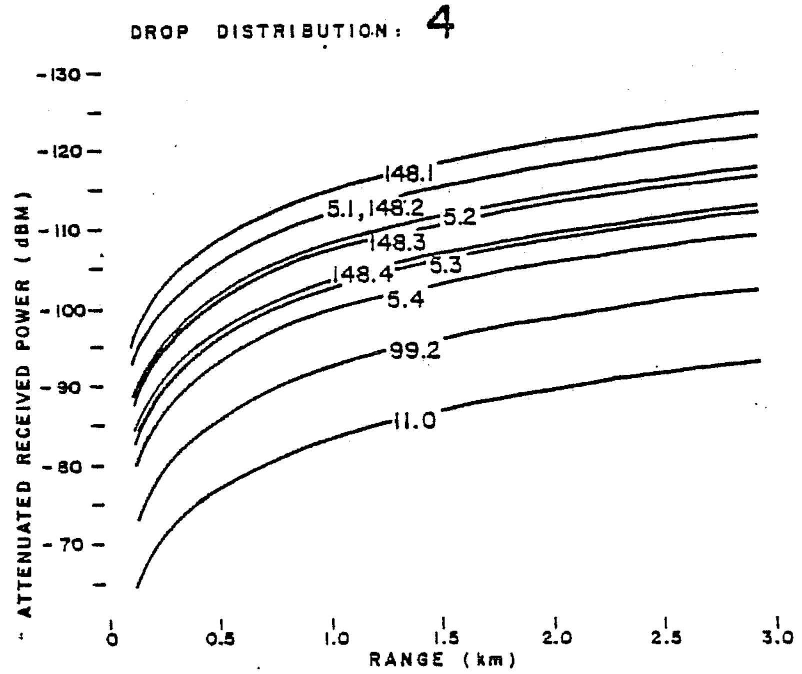

Figure 6.

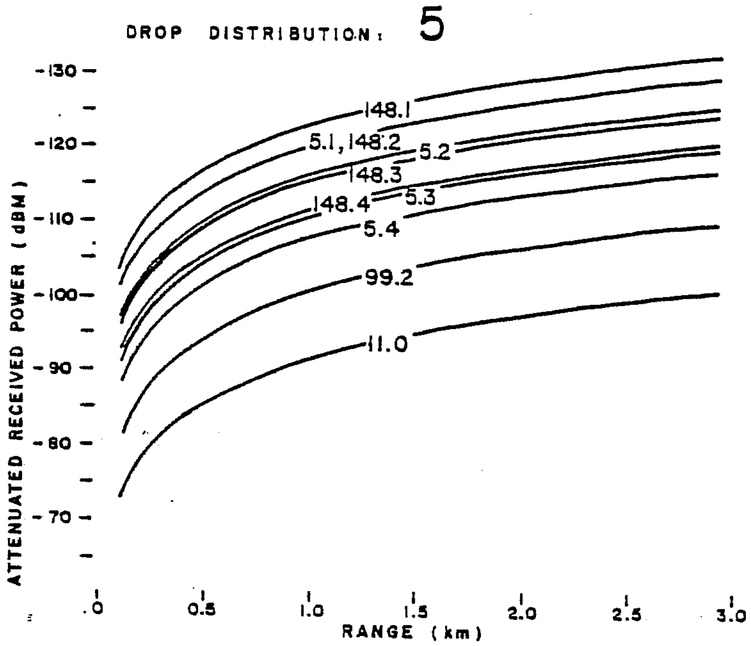

Figure 7.

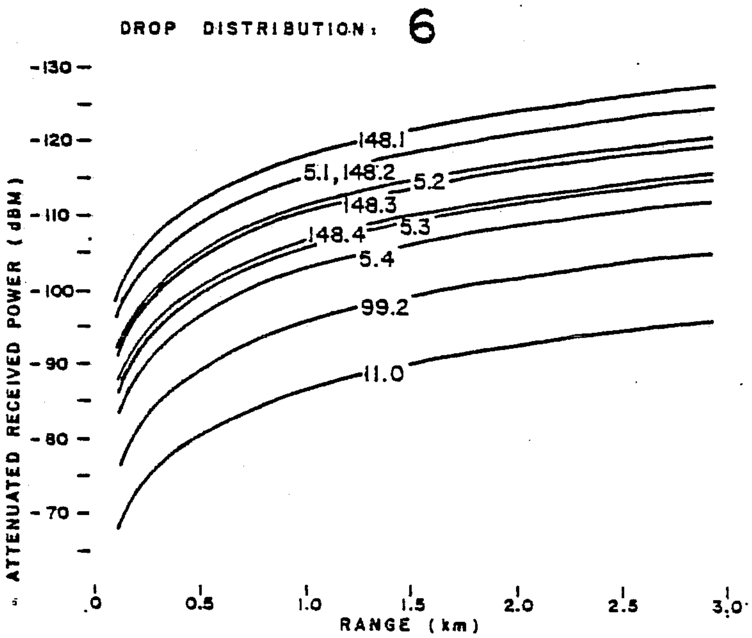

Figure 8.

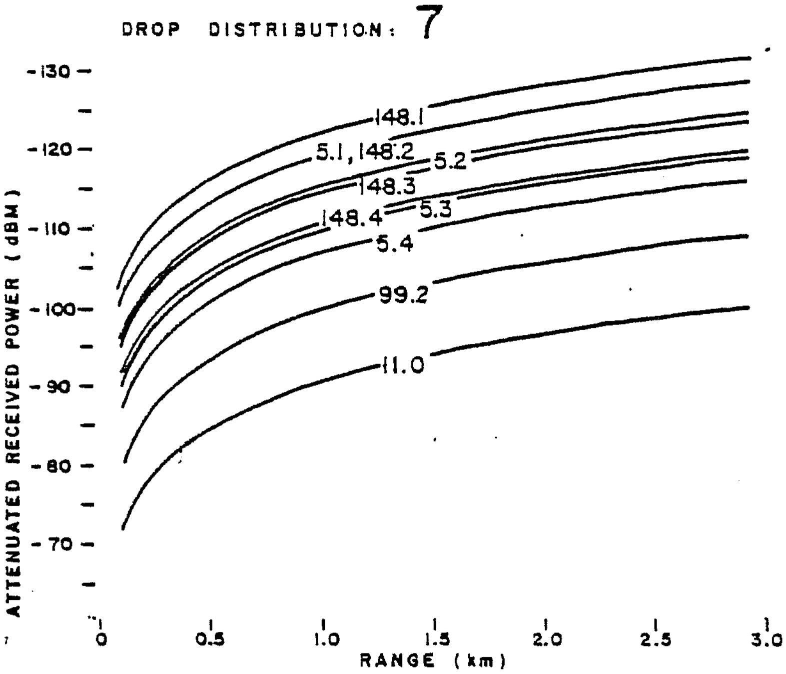
DROP DISTRIBUTION: 7
ATTENUATED RECEIVED POWER (dBM)
-130
-120
-110
-100
-90
-80
-70
148.1
5.1, 148.2
5.2
148.3
148.4
5.3
5.4
99.2
11.0
0
0.5
1.0
1.5
2.0
2.5
3.0
RANGE (km)

Figure 9.

variability in radar reflectivity sampled within a single plume and site. Such wide variations measured in adjacent aircraft penetrations indicate a complex plume structure perhaps best observable by remote sensing methods.

These sampled drop distributions are arranged from "best reflector" to "poorest reflector" in table 5. The number 6 distribution is the average case. Distributions 2, 3, and 4 are on the better side (#3 being best) and numbers 1, 5, and 7 are on the poor side (#5 being worst case). The actual calculated radar reflectivity, η, (CM^{-1}) for each drop distribution and radar type is given in table 5, where reflectivity data for naturally-occurring cloud, rain, and turbulent eddy structure is given for comparison.

Table 5. Calculated Radar Reflectivities

Drop Distribution	λ=1.87cm RC5 & APQ148	λ=1.87cm HYBRID 99.2	λ=0.87cm TPQ11
1	$.24117x10^{-13}$	$.30735x10^{-13}$	$.51476x10^{-12}$
2	$.93226x10^{-13}$	$.11881x10^{-12}$	$.19899x10^{-11}$
3	$.16360x10^{-12}$	$.20849x10^{-12}$	$.34919x10^{-11}$
4	$.11867x10^{-12}$	$.15124x10^{-12}$	$.25330x10^{-11}$
5	$.21092x10^{-13}$	$.26881x10^{-13}$	$.45021x10^{-12}$
6	$.60661x10^{-13}$	$.77308x10^{-13}$	$.12948x10^{-11}$
7	$.23972x10^{-13}$	$.30551x10^{-13}$	$.51168x10^{-12}$
Natural Cloud	$.219 \times 10^{-18}$		$.618 \times 10^{-17}$
	based on data from Fletcher (1966) Note: Actual cloud reflectivities may vary six orders of magnitude from this example		
Rainfall	$.508 \times 10^{-7}$		$.108 \times 10^{-5}$
	based on Marshall-Palmer drop distribution Battan (1973), p 95. Assuming rainfall rate of 4 mm/hr and $z = 350 R^{1.32}$		
Turbulent Eddies	$.316 \times 10^{-16}$		$.400 \times 10^{-15}$
	Battan (1973) pp 256-258 Assuming $C_n^2 = 1 \times 10^{-15}$		

Table 6 is a comparison of range performance for each radar system. The range at which the attenuated received power (as given in figures 3 through 9) equals the minimum sensible power, the range of 10 dB signal to noise ratio, and the minimum operable range are listed.

Figure 10 is a graphical comparison of the beam widths of the available radar systems as they vary with range. Because the angular resolution of the radar is determined by the width of the beam, the usable range of each radar may be determined once a minimum acceptable lateral resolution has been determined. Assuming a lateral plume dimension of 20 meters, the graph indicates a maximum usable range of 650 to 800 meters for the RC5 and APQ148 sets. The longitudinal (depth) resolution of the radar (h/2) is a function of pulse length. Table 2 indicates the desirability of combining the short pulse of the Norden sets operated in mode 1 with the narrow beam of the TPQ11.

Before further system modifications are undertaken, a comparison of the radar equation sensitivity to changes in the input parameters might be considered. Such a comparison is made in table 7. The analysis shows that modifying the antenna gain or wavelength is twice as effective as making the same percentage change in the transmitted power, beam dimensions, or pulse length. Recently obtained USAF documents list TPQ11 pulse lengths as short as 0.5 μsec and power in 80 KW range for high serial number TPQ11 sets. These improvements over the measured specifications given in table 2 (from NCAR) should be considered in further modifications feasibility analysis.

7. CONCLUSIONS

This paper has analyzed the feasibility of adapting available K-band radar systems to the study of cooling tower plumes. Two commercially available systems, the Norden RC5 and the Norden AN/APQ148, are deemed to have acceptable performance for ranges of about 500 meters for the "average" sampled plume. The beam width at that range is acceptable for resolution, but the long pulse lengths necessary to yield a detectable returned signal are prohibitively large for depth accuracy.

A surplus military system, the Olympic Radio AN/TPQ-11, was found to have acceptable performance at ranges beyond 1500 meters in terms of both returned signal strength and angular resolution. Depth resolution was limited by long (1 μ sec) pulse length, and the high maintenance costs incurred by age and magnetron replacements are additional negative factors.

A solution appears to be to adapt one of the more modern, powerful, short-pulse length Norden sets with a narrow beam, high gain antenna of the type used on the AN/TPQ11. After a set of preliminary data has been obtained with such a configuration, additional modifications allowing the investigation of polarization effects, attenuation, and more sophisticated displays may be incorporated.

Table 6. Comparative Range Performance

	Radar Model & Mode									
	5.1	5.2	5.3	5.4	148.1	148.2	148.3	148.4	11.0[2]	99.2[1]
P_{MIN} (dBm)	-98	-100	-102	-105	-98	-100	-102	-105	-100	-100
R_{MIN} (m)	500	500	500	525	500	500	500	500	152	
Drop Distribution										
1	-/-	.18/<.12	.42/<.12	.83/.27	-/-	.12/<.12	.25/<.12	.56/.18	>2.9/.97	1.05/.33
2	.18/<.12	.35/.12	.82/.27	1.67/.52	.13/<.12	.22/<.12	.48/.17	1.12/.37	>2.9/1.82	2.07/.67
3	.22/<.12	.47/.15	1.10/.35	2.17/.72	.17/<.12	.30/<.12	.65/.20	1.45/.47	>2.9/2.47	2.72/.87
4	.22/<.12	.42/.13	.92/.30	1.87/.62	.15/<.12	.27/<.12	.47/.15	.87/.27	>2.9/2.07	2.32/.75
5	-/-	.17/<.12	.42/.13	.79/.25	-/-	-/-	.25/<.12	.52/.17	2.7/.92	.97/.32
6	.15/<.12	.30/<.12	.67/.22	1.37/.42	-/-	.19/<.12	.40/.13	.87/.27	>2.9/1.52	1.67/.52
7	-/-	.17/<.12	.42/.13	.86/.27	-/-	-/-	.25/<.12	.55/.19	2.86/.97	1.05/.33

Legend:

Range where attenuated received power equals minimum sensible power (km)	/	Range where signal to noise ratio = 10 dB

Notes:

1. Radar 99.2 assumes pulse character of Norden RC5.1 with antenna gain and beam dimensions of AN/TPQ-11
2. Other publications list TPQ-11 specs of P_T = 80 kw (vs 25 kw used here).

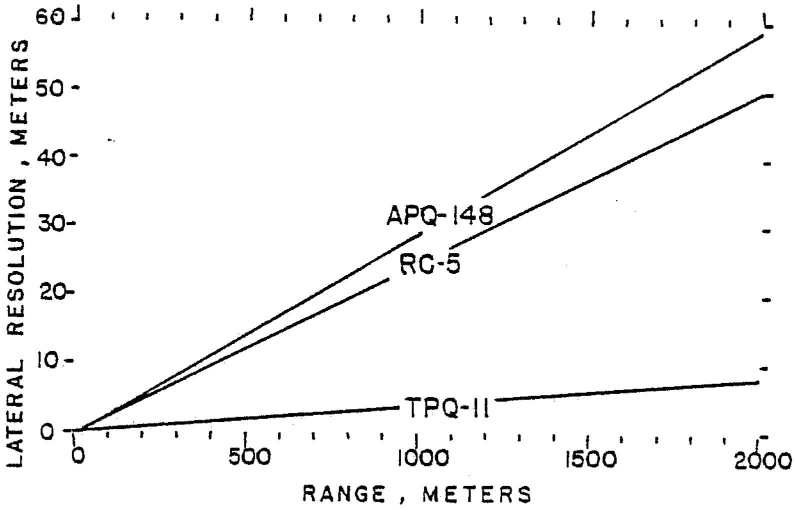

Figure 10. Angular resolution versus range for available K-band radar systems.

Table 7. Radar Parameter Sensitivity Analysis

Technique:

To find ΔP_R (P_T, G, λ, θ, ϕ, h, r, η)

using: $$P_R = \frac{P_T\, G^2\, \lambda^2\, \theta\, \phi\, h}{512(2\ln 2)\pi^2\, r^2}\, \eta$$

$$\Delta P_R = \frac{\Delta P_R}{\Delta P_T}\, \Delta P_T + \frac{\Delta P_R}{\Delta_G}\, \Delta G + \ldots\ldots$$

replacing $\frac{\Delta P_R}{\Delta i}$ by $\frac{dP_R}{di}$ and using parameter values from RC5.1 and Keystone #1

Parameter	Change in P_R per *	Change in P_R per 1/10 change in radar parameter
P_T	5.41×10^{-21} * = Watt	3.25×10^{-17}
G	2.09×10^{-19} * = Unit gain	6.49×10^{-17}
λ	3.47×10^{-16} * = cm (attenuation not considered)	6.49×10^{-17}
θ	2.71×10^{-14} * = Radian	3.25×10^{-17}
ϕ	1.29×10^{-14} * = Radian	3.25×10^{-17}
h	5.41×10^{-20} * = cm	3.25×10^{-17}
r	3.25×10^{-21} * = cm	6.49×10^{-17}
η	1.35×10^{-2} * = cm^{-1}	3.25×10^{-17}

8. SUGGESTIONS FOR FURTHER RESEARCH

This paper has identified the feasibility of adapting commercially available non-coherent, pulsed K-band radar systems as a means of obtaining needed plume data. In the introductory portions of the paper several research problems, some of an urgent nature, were suggested as possible beginning points. Before such research may be pursued, additional theoretical feasibility checks need to be made. Because order of magnitude performance estimates involving polarization, attenuation by gaseous pollutants, and variable frequency systems require initial measurements, it is also desirable to acquire and adapt hardware of the type referenced in this paper.

The first recommendation, then, is to obtain an operational system and after making the necessary adaptations, to begin taking plume measurements correlating the radar data with in situ sampling, where possible. In this way, a basic data base may be established.

Once this has been done, contouring options available on several radar systems may be combined with knowledge of differences in plume density and reflectivity to yield a means of successfully locating and studying the problem of plumes embedded within natural clouds.

Antenna modifications may also be made once the basic concept and hardware has been demonstrated and refined. This will allow better analysis of the plume freezing processes as they change with time and distance.

Additional progress continues to be made in the areas of microwave interaction with gaseous contaminants. Raman lidar will also undoubtedly continue as a potent tool in this field, but because of its requirements for darkness and more sophisticated receptors, applications of microwave systems to this field should continue. Perhaps study sites in areas of more dense gaseous plumes (such as an operating smelter) might offer better opportunities for initial research.

An FMCW radar system of the type built by NOAA Wave Propagation Laboratories offers many of the characteristics required for research in these more advanced areas. Its minimum range may be as short as 60 meters (Strauch, et al, 1975).

A final suggestion would be to compile the accumulating data dealing with thermal plumes into a workbook suitable for meteorologists and environmental engineers. Such a reference work might include data on plume rise, drop distributions for the plume and drift, deposition, and the insight gained by these additional studies.

ACKNOWLEDGEMENTS

I gratefully acknowledge the assistance of the following persons and organizations, each of whom contributed to the completion of this report. Dr. Dennis W. Thomson, Department of Meteorology, Pennsylvania State University, for his guidance and suggestions; Mr. C. Ray Dickson, and the NOAA Air Resources Laboratories, for the time and equipment made available to the project; Dr. Jorge Pena for making available the unpublished sampled plume data; to Messers. Art Levitan and Dick Briones of Norden Division of United Technologies Corporation, for the specifications of their radar products, and to SMSgt- Harbuck, HQ, Air Weather Service, USAF, for data and useful procurement information on the TPQ11 system.

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Appendix I. Military Equipment Designations

Set or equipment indicator letters

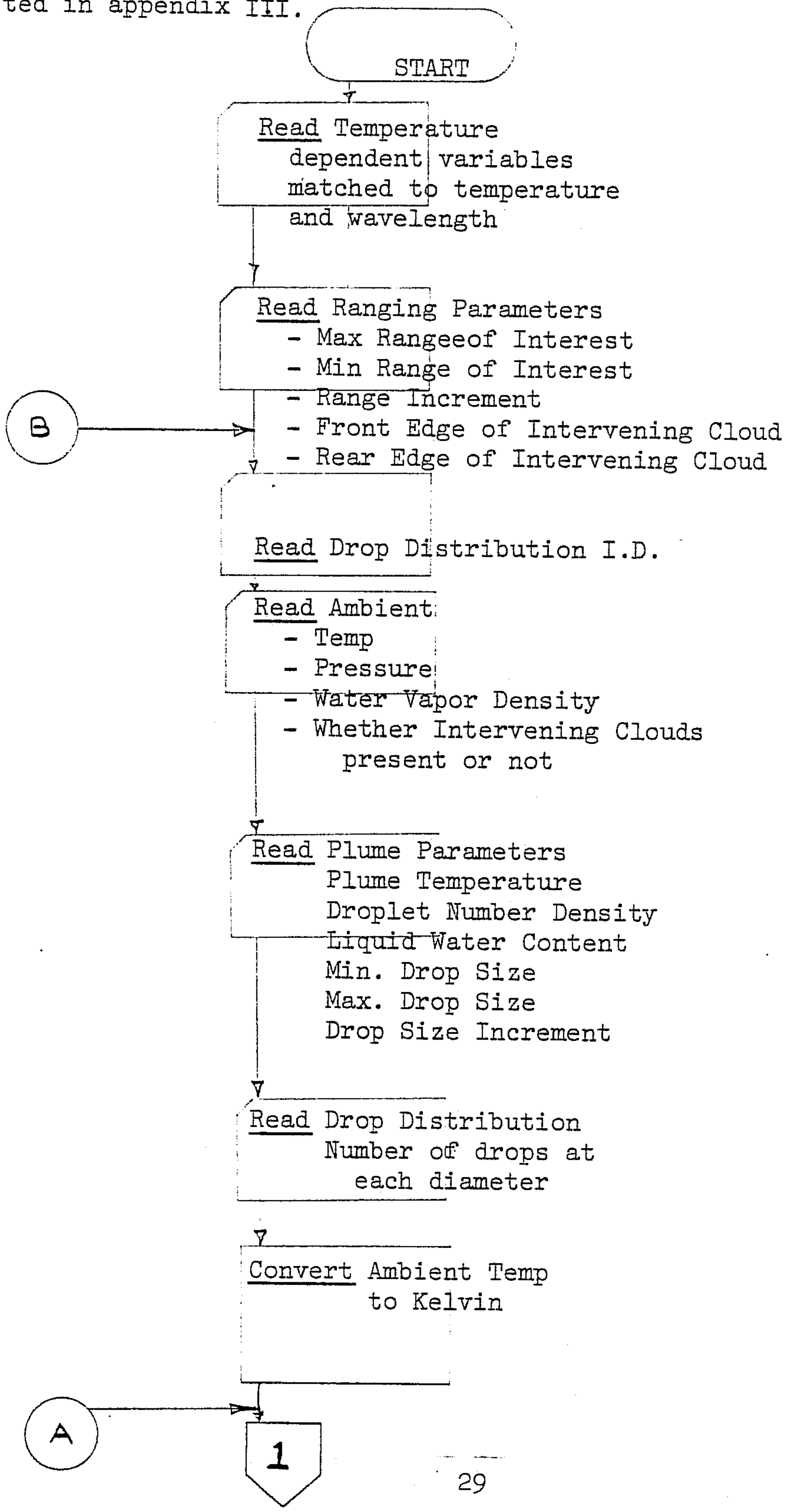
type of installation	type of equipment	purpose
A Airborne (installed and operated in aircraft)	A Invisible light, heat radiation	A Auxiliary assemblies (not complete operating sets used with or part of two or more sets or sets series)
B Underwater mobile, submarine	B Pigeon	B Bombing
C Air transportable (inactivated, do not use)	C Carrier	C Communications (receiving and transmitting)
D Pilotless carrier	D Radiac	D Direction finder and/or reconnaissance
	E Nupac	E Ejection and/or release
F Fixed	F Photographic	
G Ground, general ground use (includes two or more ground type installations)	G Telegraph or teletype	G Fire control or searchlight directing
		H Recording and/or reproducing (graphic meteorological and sound)
	I Interphone and public address	
	J Electro-mechanical (not otherwise covered)	
K Amphibious	K Telemetering	
	L Countermeasures	L Searchlight control (inactivated, use "G")
M Ground, mobile (installed as operating unit in a vehicle which has no function other than transporting the equipment)	M Meteorological	M Maintenance and test assemblies (including tools)
	N Sound in air	N Navigational aids (including altimeters, beacons, compasses, racons, depth sounding, approach, and landing)
P Pack or portable (animal or man)	P Radar	P Reproducing (inactivated, do not use)
	Q Sonar and underwater sound	Q Special, or combination of purposes
	R Radio	R Receiving, passive detecting
S Water surface craft	S Special types, magnetic, etc., or combinations of types	S Detecting and/or range and bearing
T Ground, transportable	T Telephone (wire)	T Transmitting
U General utility (includes two or more general installation classes, airborne, shipboard, and ground)		
V Ground, vehicular (installed in vehicle designed for functions other than carrying electronic equipment, etc., such as tanks)	V Visual and visible light	
W Water surface and underwater	W Armament (peculiar to armament, not otherwise covered)	W Control
	X Facsimile or television	X Identification and recognition

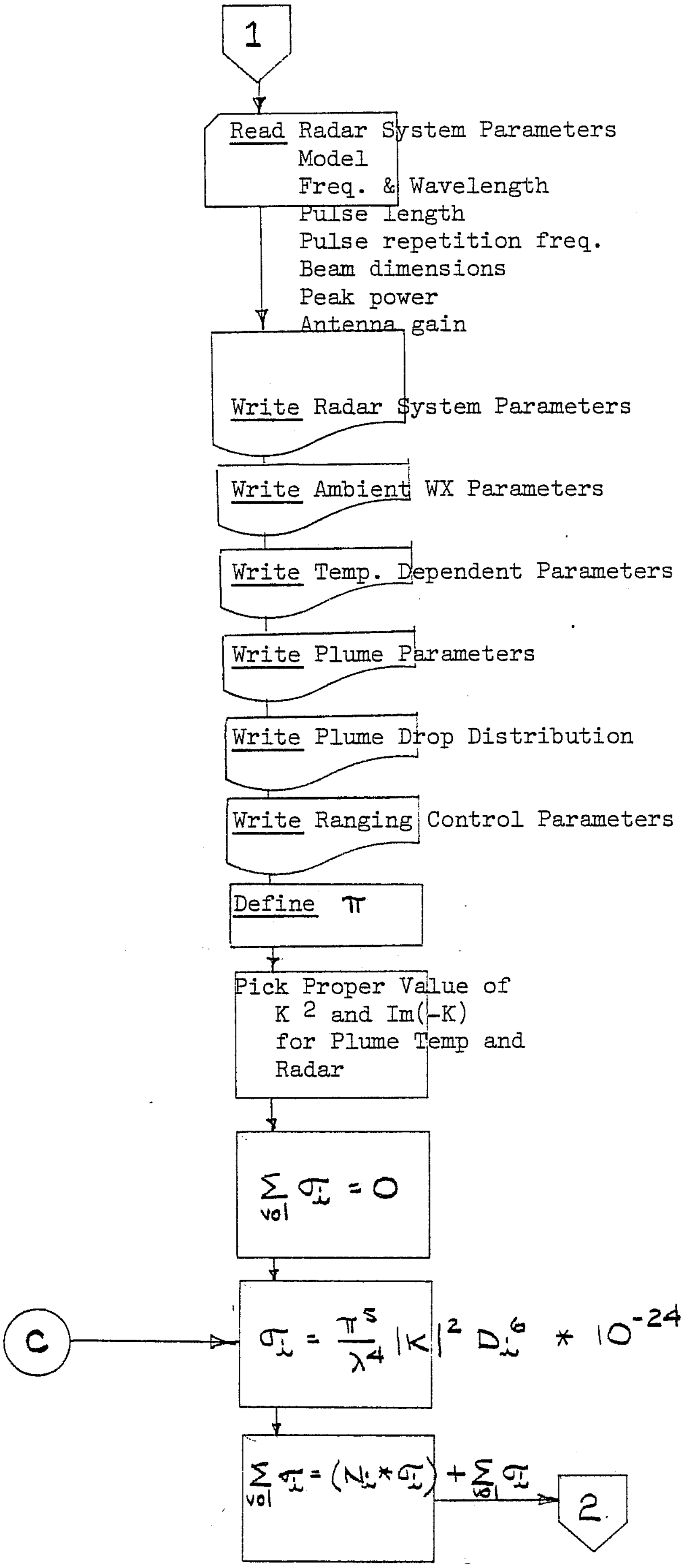
Page 959, Reference data for Radio Engineers, 4th Ed. (1967), IT&T Corp., New York.

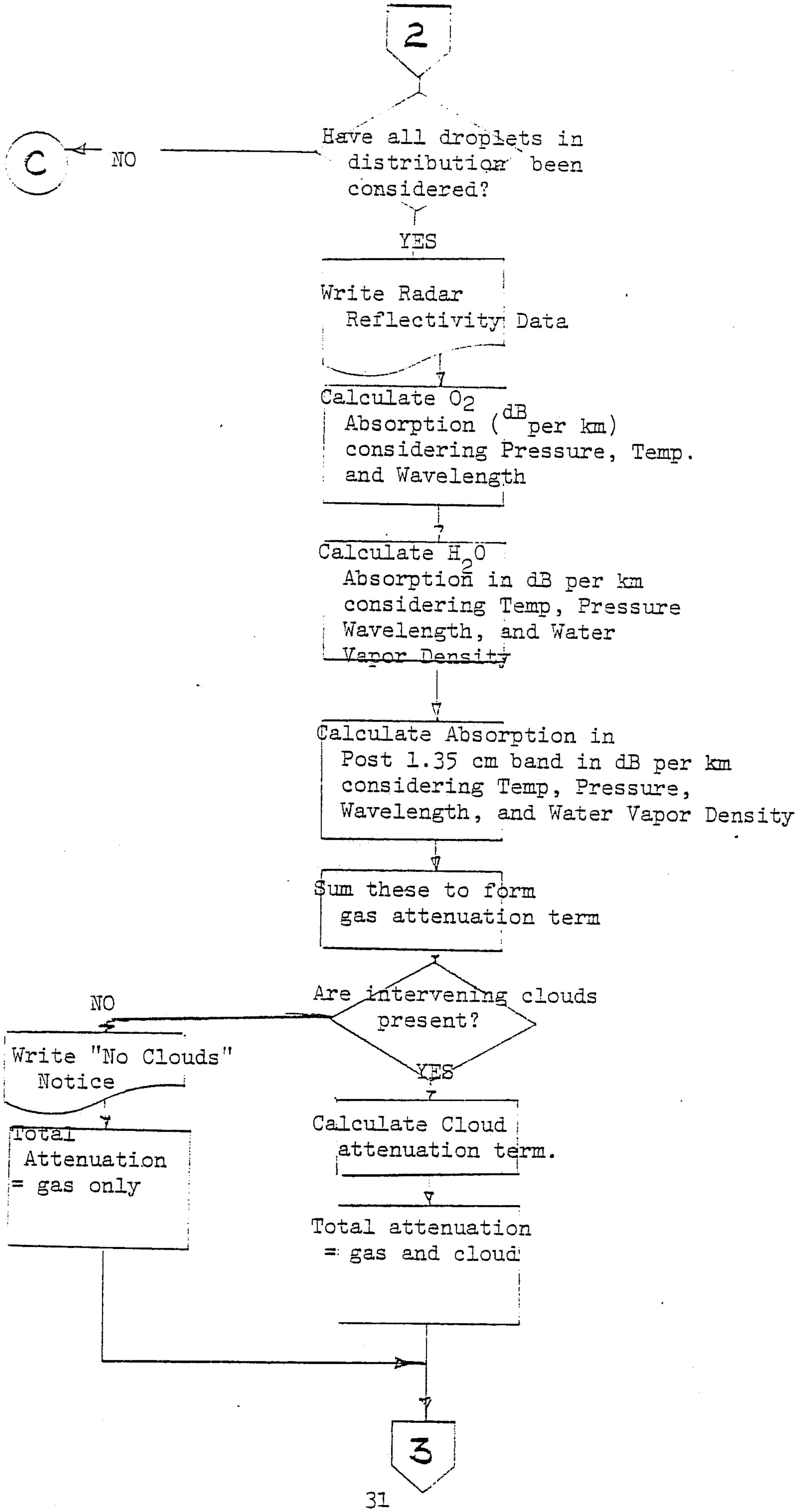
Appendix II.

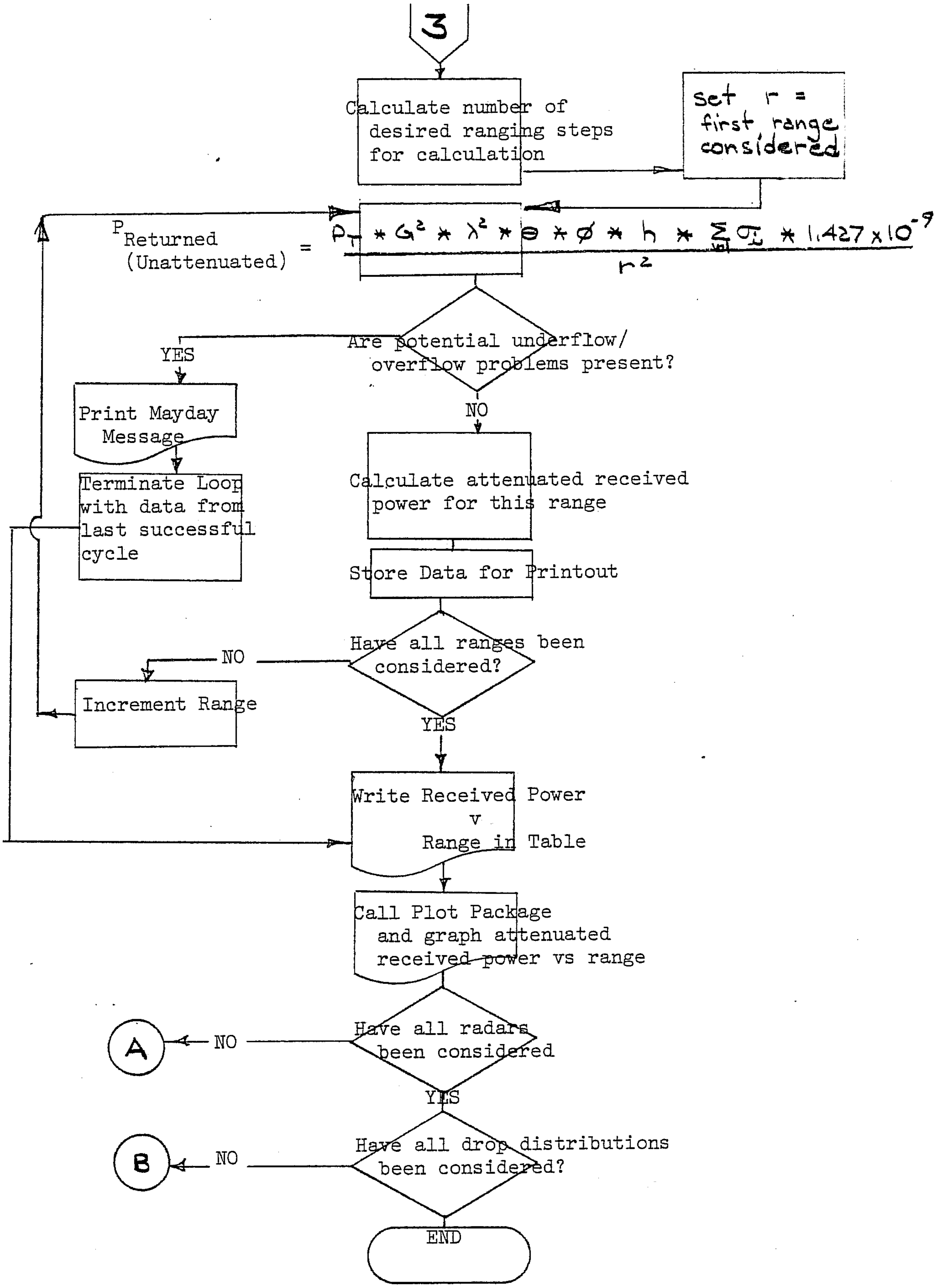
PROGRAM FLOWCHART

The following simplified flowchart documents the means by which the program calculates the expected returned signal for each radar and drop distribution. The complete program, together with the appropriate comments, is listed in appendix III.




1
Read Radar System Parameters
Model
Freq. & Wavelength
Pulse length
Pulse repetition freq.
Beam dimensions
Peak power
Antenna gain
Write Radar System Parameters
Write Ambient WX Parameters
Write Temp. Dependent Parameters
Write Plume Parameters
Write Plume Drop Distribution
Write Ranging Control Parameters
Define π
Pick Proper Value of K^2 and Im(-K) for Plume Temp and Radar
$\sum_{vol} \sigma_i = 0$
C
$\sigma_i = \frac{\pi^5}{\lambda^4} |K|^2 D_i^6 * 10^{-24}$
$\sum_{vol} \sigma_i = (N_i * \sigma_i) + \sum_{vol} \sigma_i$
2


2
Have all droplets in distribution been considered?
NO
C
YES
Write Radar Reflectivity Data
Calculate O_2 Absorption ($\frac{dB}{}$ per km) considering Pressure, Temp. and Wavelength
Calculate H_2O Absorption in dB per km considering Temp, Pressure Wavelength, and Water Vapor Density
Calculate Absorption in Post 1.35 cm band in dB per km considering Temp, Pressure, Wavelength, and Water Vapor Density
Sum these to form gas attenuation term
Are intervening clouds present?
NO
Write "No Clouds" Notice
Total Attenuation = gas only
YES
Calculate Cloud attenuation term.
Total attenuation = gas and cloud
3


3
Calculate number of desired ranging steps for calculation
set r = first range considered
P Returned (Unattenuated) = $\frac{P_T * G^2 * \lambda^2 * \theta * \phi * h * \sum \sigma_i * 1.427 \times 10^{-9}}{r^2}$
Are potential underflow/ overflow problems present?
YES
Print Mayday Message
Terminate Loop with data from last successful cycle
NO
Calculate attenuated received power for this range
Store Data for Printout
Have all ranges been considered?
NO
Increment Range
YES
Write Received Power v Range in Table
Call Plot Package and graph attenuated received power vs range
Have all radars been considered
NO
A
YES
Have all drop distributions been considered?
NO
B
END

Appendix III. Program Listing

```
PROGRAM VARIABLES DEFINED


AAC IS EXPONENT IN ATTENUATION CALCULATION
    ATNDB  IS ATTENUATION EXPRESSED IN DB LOSS
ATNDRG IS ARRAY CONTAINING ATTENUATION IN DB VS RANGE
CLDCK IS CHARACTOR TO SPECIFY INTERVENING CLOUD
    CLDFE  IS RANGE OF FRONT EDGE OF OTHER (NCN PLUME) CLOUD IN KM
    CLDRE  IS RANGE OF REAR  EDGE OF OTHER (NON PLUME) CLOUD IN KM
DBMARG IS ARRAY CONTAINING ATTEN. REC. PWR. IN DBM VS RANGE
DBMRG IS ARRAY CONTAINING UNATTEN. REC. PWR. IN DBM VS RANGE
    DELNU1 IS EMPIRICAL TEMP&PRESSURE DEPENDENT TERM,SEE BEAN ET AL 1969
    DELNU2 IS EMPIRICAL TEMP&PRESSURE DEPENDENT TERM,SEE BEAN ET AL 1969
    DELNU3 IS EMPIRICAL TEMP&PRESSURE DEPENDENT TERM,SEE BEAN ET AL 1969
    DI     IS DROPLET DIAMETER AS FOUND IN DISTRIBUTION ARRAY,MICRONS
    FE     IS BEAM HEIGHT IN RADIANS

    G      IS ANTENNA GAIN OVER ISOTROPIC
    GAM1   IS ATTENUATION BY ABSORBTION BY O2 IN DB/KM
GAM1A,GAM1B, GAM1C ARE COMPONENTS OF GAM1 EQUATION
    GAM2   IS ATTENUATION BY ABSORBTION BY H2O VAPOR IN DB/KM
GAM2A,GAM2B  ARE COMPONENTS OF GAM2 EQUATION
    GAM3   IS ATTENUATION BY ABSORBTION BY GASSES IN POST 1.35 CM BAND
             IN DB/KM

    H      IS PULSELENGTH IN METERS
I      IS DO LOOP INDEX FOR DROP DISTRIBUTION CALCULATIONS
IDRPID IS DROP DISTRIBUTION I.D. NUMBER
INDEX IS DUMMY TO SPECIFY TEMP DEP ARRAY SIZE
 J IS INDEX USED TO FILL PR,PRO VS RANGE ARRAYS
JAN IS DUMMY IN RADAR MODEL DO LOOP
JANE IS DUMMY IN DROP DISTRIBUTION DO LOOP
JBIRD1,JBIRD2 ARE DUMMYS IN TEMP DEPENDENT VARIABLE SEARCH
JDEX  IS DUMMY TO SPECIFY TEMP DEP ARRAY SIZE
JDEX3 IS DO LOOP INDEX FOR DROP DISTRIBUTION CALCULATIONS
JEND IS DUMMY USED IN ARRAY PRINTOUT
K IS INDEX USED TO PRINT PR,PRO VS RANGE ARRAYS

    NDDEL  IS INCREMENT OF DROPLET DIAMETER USED IN STEPPING THROUGH
               DROPLET DISTRIBUTION ARRAY
    NDMAX  IS MAXIMUM CLOUD DROPLET DIAMETER IN MICRONS
    NDMIN  IS MINIMUM CLOUD DROPLET DIAMETER IN MICRONS
NRDEL IS INTEGER NO OF RANGE STEPS TO BE USED

    P      IS AMBIENT PRESSURE IN MB
```

```
    PI      IS 3.1416 ETC
    PMIN    IS MINIMUM SENSIBLE RECEIVED POWER  IN DBM
PPPPRO IS PR IN MW
    PR      IS FINAL RECEIVED POWER (INCLUDING ATTENUATION) IN WATTS
PREDBM IS ATTENUATED RECEIVED POWER IN DBM
PREPRO IS PRO IN MW
PREPRR IS PR/PRO
    PRF     IS PULSE REPITION FREQ IN PER SECOND
    PRO     IS RECEIVED POWER BEFORE ATTENUATION            IN WATTS
    PRODBM IS POWER BEFORE ATTENUATION IN DB BELOW MILLIWATT
PRORG IS ARRAY CONTAINING UNATTENUATED REC.PWR IN WATTS VS RANGE
PRRG IS ARRAY CONTAINING ATTEN. REC. PWR. IN WATTS VS RANGE
    PT      IS PEAK TRANSMITTED POWER IN KILOWATTS
    QSGVOL IS SCATTERING CROSS SECTION FOR EACH DROPLET IN CM2
    R       IS ACTUAL TARGET RANGE UNDER STUDY, IN KM
RG IS RANGE ARRAY MATCHED FOR PRINTOUT
    RMAX     IS RADAR MAX RANGE LIMITED BY TAU AND PRF IN KM
    RMODEL IS RADAR MODEL AND MODE:  NORDEN RC5 MODE 1 CODED"5.1"
                                     NORDEN APQ-148 MODE 2 AS "148.2"
                                            AN-TPQ-11 AS"11.0"
    RO      IS WATER VAPOR DENSITY IN GRAMS PER M3
    RRDEL   IS STEPPING INCREMENT  IN RANGE INVESTIGATION, IN KM
    RRMAX   IS MAX RANGE OF INTEREST IN INVESTIGATION,IN KM
    RRMIN   IS MIN RANGE OF INTEREST IN INVESTIGATION,IN KM

    SIGVOL IS RADAR REFLECTIVITY IN CM-1 AND IS QSGVOL SUMMED OVER ALL
              PARTICLES
    T      IS AMBIENT ( NON PLUME ) TEMP IN CELSIUS
    TAU IS PULSELENGTH IN MICROSECONDS
    THETA  IS BEAM WIDTH IN RADIANS
    TT      IS PLUME TEMP, IN CELSIUS
    TT1     ISTEMP FOR XK2,XIMK  IN CELSIUS

X1,X2,X3,X4 ARE COMPONENTS OF PRO EQUATION
    XIMK    IS IMAGINARY PERT OF -K...A TEMP AND FREQ DEPENDENT
      ABSORBTION TERM
    XK      IS TOTAL ATTENUATION IN DB/KM
    XKCLD   IS ATTENUATION BY INTERVENING CLOUD PARTICLES IN DB/KM
    XKGAS   IS SUM OF O2,H2O,&GT.1.35CM GAS ABSORBTION IN DB/KM
    XKI1    IS EMPIRICAL TEMP&PRESSURE DEPENDENT TERM,SEE BEAN ET AL 1969
    XKI2    IS EMPIRICAL TEMP&PRESSURE DEPENDENT TERM,SEE BEAN ET AL 1969
    XK2     IS ABSOLUTE VALUE OF K**2,; A TEMP AND FREQ DEPENDENT
      SCATTERING TERM
    XKONE   IS TEMP DEPENDENT DROPLET ABSORBTION PARAMETER
    XLAM1   IS WAVELENGTH FOR XK2,XIMK   IN CM
    XLAMDA IS WAVELENGTH IN CM
    XN      IS CLOUD DROPLET CONCENTRATION IN NUMBER PER CM3
    XNI     IS IS CONCENTRATION OF DROPLETS OF SIZE DI   IN UNITS OF
        NUMBER PER CM3
    XNU     IS FREQUENCY IN GHZ
    XM      IS CLOUD LIQUID WATER CONTENT IN GRAMS PER METER3


DIMENSION XK2(20),XIMK(20),TT1(20),XLAM1(20)
```

```
      DIMENSION DI(110),XNI(110)
      DIMENSION  RG(400),PRORG(400),PRRG(400),ATNDRG(400),DBMRG(400)
       DIMENSION DBMARG(400)
      DO 20 INDEX=1,20
      READ(5,102) XK2(INDEX),TT1(INDEX),XLAM1(INDEX),XIMK(INDEX)
C      READS TEMP DEPENDENT PARAMETERS( BATTAN 1973)
  102 FORMAT(4F10.0)
   20 CONTINUE
C     102 FORMAT CONTROLS TEMP DEPENDENT PARAMETERS MATCHED TO TEMP
C         AND WAVELENGTH
      READ(5,105) RRMIN,RRMAX,RRDEL,CLDFE,CLDRE
C     RRDEL USUALLY =H/2,GIVING CONTINUOUS SPACE COVERAGE
  105 FORMAT(5F10.0)
C     105 FORMAT CONTROLS RANGING PARAMETERS:MIN AND MAX RANGES OF
C         INTEREST,RANGE INCREMENT,RANGES OF CLOUD FRONT AND REAR EDGES
      DO 3006  JANE=1,7
      READ (5,21)  IDRPID
C      IDRPID IS DROP DISTRIBUTION NUMBER
   21 FORMAT (I5)
      READ(5,101)T,P,RO,CLDCK
C      101 FORMAT CONTROLS WX PARAMETERS EXTERNAL TO PLUME
  101 FORMAT(4F10.0)
C      CLDCK=0 IF NO (NON PLUME) CLOUDS PRESENT
      READ(5,103) TT,XN,XM,NDMIN,NDMAX,NDDEL
  103 FORMAT(3F5.0,3I5)
C     103 FORMAT CONTROLS ACTUAL PLUME TEMP TT,DROPLET NUMBER DENSITY
C        XN,CLOUD LIQUID WATER CONTENT XM,,MIN,MAX,AND DELTA DROP SIZE
      DO 30 INDEX3=NDMIN,NDMAX,NDDEL
      READ(5,104) DI(INDEX3),XNI(INDEX3)
  104 FORMAT(2F10.0)
   30 CONTINUE
      T=T+273.16
C     104 FORMAT CONTROLS DROP SIZE DISTRIBUTION:DIA IN MICRONS VS
C         NUMBER PER CC
       DO 357  JAN=1,9
    4 READ(5,100,        )RMODEL,XNU,XLAMDA,TAU,H,PRF,RMAX,THETA,FE,PT,
     1G,PMIN
C     100 FORMAT CONTROLS RADAR PARAMETERS
  100 FORMAT(10F5.0,F10.0,F5.0)
C      INPUT DATA IS PRINTED FOR CHECK AND DOCUMENTATION
       WRITE(6,200)RMODEL,XNU,XLAMDA,TAU,H,PRF,RMAX,THETA,FE,PT,G,PMIN
  200 FORMAT('1','COOLING TOWER PLUME RADAR ANALYSIS PROGRAM'/' ','RADAR
     1 PARAMETERS:'/1X,5X,'RADAR MODEL CONSIDERED:',F12.4/1X,5X,'FREQUEN
     2CY,GHZ:',F12.4/1X,5X,'WAVELENGTH,CM:',F12.4/1X,5X,'PULSE LENGTH,MI
     3CROSECONDS:',F12.4/1X,5X,'PULSE LENGTH, METERS:',F12.4/1X,5X,
     4'PULSE REPETITION FREQUENCY(PRF):',F12.4/1X,5X,'MAXIMUM THEO. RANG
     5E, KM  :',F12.4/1X,5X,'BEAM WIDTH IN RADIANS:',F12.4/1X,5X,'BEAM H
     6EIGHT IN RADIANS:',F12.4/1X,5X,'PEAK TRANSMITTED POWER IN KW:',F12
     7.4/1X,5X,'ANTENNA GAIN OVER ISOTROPIC:',F12.4/1X,5X,'MINIMUM RECEI
     8VABLE POWER, DBM :',F12.4///)
       WRITE(6,201) T,P,RO
  201 FORMAT(1X,'WEATHER PARAMETERS EXTERNAL TO PLUME'/1X,5X,'AIR TEMPER
     1ATURE,KELVIN ',F12.4/1X,5X,'PRESSURE;MILLIBARS:',F12.4/1X,5X,'WATE
     2R VAPOR DENSITY,GRAMS PER CUBIC METER:',F12.10///)
       WRITE(6,202)
  202 FORMAT(1X,'TEMPERATURE DEPENDENT PARAMETERS'/1X,5X,'XK2',5X,'XLAM1
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     1',5X,'TT1',5X,'XIMK'/)
      DO 40 JDEX=1,20
      WRITE(6,203)XK2(JDEX), XLAM1(JDEX),TT1(JDEX),XIMK(JDEX)
  203 FORMAT(1X,4F9.4/)
   40 CONTINUE
      WRITE(6,204)TT,XN,XM,NDMIN,NDMAX,NDDEL
  204 FORMAT(1X,//1X,'INTERNAL PLUME PARAMETERS',/1X,5X,'PLUME TEMPERATU
     1RE,CELSIUS:',F8.4/1X,5X,'DROPLET NUMBER DENSITY,NUMBER PER CUBIC C
     2ENTIMETER:',F8.1/1X,5X,'CLOUD LIQUID WATER CONTENT,GRAMS PER CUBIC
     3 METER:',F8.4/1X,5X,'MINIMUM DROPLET DIAMETER,MICRONS:',I8/1X,5X,
     4'MAXIMUM DROPLET DIAMETER,MICRONS:',I8/1X,5X,'INCREMENTAL DIAMETER
     5 CHANGE,MICRONS:',I8///)
      WRITE(6,205)
  205 FORMAT(1X,'CLOUD DROP DISTRIBUTION DATA'/1X,5X,'DROP',7X,'NUMBER'/
     11X,3X,'DIAMETER',5X,'PER CM3'/1X,'(MICRONS)',//)
      DO 50 JDEX3=NDMIN,NDMAX,NDDEL
      WRITE(6,206) DI(JDEX3),XNI(JDEX3)
  206 FORMAT(1X,F10.4,F13.4/)
   50 CONTINUE
      WRITE(6,207) RRMIN,RRMAX,RRDEL,CLDFE,CLDRE
  207 FORMAT(1X,//1X,'RANGING PARAMETERS',/1X,5X,'MINIMUM RANGE OF INTER
     1EST,KM',F12.4/1X,5X,'MAXIMUM RANGE OF INTEREST,KM:',F12.4/1X,5X,
     2'RANGE STEPPING INCREMENT,KM:',F12.4/1X,5X,'RANGE OF FRONT EDGE OF
     3INTERVENING CLOUD,KM:',F12.4/1X,5X,'RANGE OF REAR EDGE OF INTERVEN
     4ING CLOUD,KM:',F12.4///)
      PI=3.141592654
C
C       THE FIRST STEP IS TO CALCULATE THE SCATTERING CROSS SECTION FOR
C         EACH DISCRETE DROP SIZE,AND ADD CONTRIBUTIONS FROM EACH DROP SIZE
C           INTERVAL TO FORM A TOTAL REFLECTIVITY
C
      SIGVOL=0
C      THE FOLLOWING 9 IF STATEMENTS PICK PROPER TEMP DEPENDENT VARIABLES
C
      IF (TT.GE. 15.0) JBIRD1=5
      IF (TT.GE.  5.0) JBIRD1=10
      IF(TT.GE. -4.0) JBIRD1=15
      IF(TT.LT. -4.0) JBIRD1=20
C
      IF(XLAMDA.GE. 2.54) JBIRD2=JBIRD1
      IF(XLAMDA.GE. 1.555)JBIRD2=JBIRD1-1
      IF(XLAMDA.GE. 1.055)JBIRD2=JBIRD1-2
      IF(XLAMDA.GE.  .745)JBIRD2=JBIRD1-3
      IF(XLAMDA.LT.  .745)JBIRD2=JBIRD1-4
C
      DO 60 I=NDMIN,NDMAX,NDDEL
      QSGVOL=(PI**5)*(XLAMDA**(-4))*XK2(JBIRD2)*(DI(I)**6)
      QSGVOL=QSGVOL*1.0E-24
      SIGVOL=QSGVOL*XNI(I)+SIGVOL
C      CALCULATED RADAR REFLECTIVITIES ARE LISTED
      WRITE(6,991) QSGVOL,XNI(I),SIGVOL
  991 FORMAT (1X,3E16.5,/)
   60 CONTINUE
C        AT THIS POINT SIGVOL IS TOTAL SUMMED REFLECTIVITY
C
C     ATTENUATION COMPUTATIONS FOLLOW
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C      FORMULAS TAKEN FROM BEAN ET AL 1969
C       GAM1 IS O2 ABSORBTION IN DB PER KILOMETER
C      XKI1,DELNU1,&DELNU2 ARE EMPIRICAL TEMP AND PRESSURE DEPENDENT TERMS
      XKI1=((.34*P)/(1013.25*(XLAMDA**2)))*(293.0/T )**2
      DELNU1=((.018*P)/1013.25)*(293.0/T )**.75
      DELNU2=((.049*P)/1013.25)*(300.0/T )**.75
      GAM1A=(DELNU1/((XLAMDA**(-2))+(DELNU1**2)))
      GAM1B=(DELNU2/(((2.+(1./XLAMDA))**2)+(DELNU2**2)))
      GAM1C=(DELNU2/(((2.-(1./XLAMDA))**2)+(DELNU2**2)))
      GAM1=XKI1*(GAM1A+GAM1B+GAM1C)
C      GAM2 IS H2O VAPOR ABSORBTION IN DB PER KM
C      XKI2,DELNU3 ARE EMPIRICAL TEMP&PRESSURE DEPENDENT TERMS
      XKI2=.0318*(XLAMDA**(-2))*((293.0/T )**2.5)*(EXP(-644.0/T ))
      DELNU3=((.087*P)/1013.25)*((318.0/T )**.5)*(1+(.0046*RO))
      GAM2A=(DELNU3/(((1./XLAMDA)-.741)**2 +(DELNU3**2)))
      GAM2B=(DELNU3/(((1./XLAMDA)+.741)**2 +(DELNU3**2)))
      GAM2=RO*XKI2*(GAM2A+GAM2B)
C      GAM3 IS GAS ABSORBTION ABOVE 1.35 CM BAND, EFFECTIVE HERE DUE TO
C      PRESSURE BROADENING EFFECTS
      GAM3A=((.087*P)/1013.25)
      GAM3B=(318.0/T )**.5
      GAM3C=(1.+(.0046*RO))
      GAM3=RO*.05*(XLAMDA**(-2))*(293.0/T )*GAM3A*GAM3B*GAM3C
C      XKGAS IS SUM OF O2,H2O,& MISC GAS ABSORBTION
      XKGAS=GAM1+GAM2+GAM3
C      PARTICLE ATTENUATION BY INTERVENING CLOUD IS HANDLED
C      BY XKCLD: UNITS ARE DB PER KM
      IF(CLDCK.EQ. 0.)  GO TO 1200
      XKONE=(8.186362/XLAMDA)*XIMK(JBIRD2)
      XKCLD=XKONE*XM
      XK=XKCLD+XKGAS
      GO TO 1201
 1200 XK=XKGAS
      WRITE(6,1202)
 1202 FORMAT(1X,'**** NO INTERVENING CLOUDS...NO RESULTING ATTENUATION',
     1 //)
C      ATTENUATION DATA LISTED FOR CHECK
 1201  WRITE(6,992) GAM1,GAM2,GAM3,XKGAS,XK
  992  FORMAT(1X,5E16.5,/)
      NRDEL=(RRMAX-RRMIN)/RRDEL
C       RANGE INCREMENTING DO LOOP TO START HERE
      DO 300  J=1,NRDEL
      R=RRMIN+(J-1)*RRDEL
      X1=PT*(G**2)
      X2=(XLAMDA**2)*THETA
      X3=FE*H*SIGVOL
      X4=(R**(-2))*1.427 E-9
      PRO=X1*X2*X3*X4
C      NOW BEGINS THE CALCULATION OF COMBINED ATTENUATION EFFECTS ON
C      PREVIOUSLY UNATTENUATED RECEIVED POWER (PRO)
      AAC=(-.2*XK*R)
C      FOLLOWING 3 IFS CHECK FOR POTENTIAL OVERFLOW/UNDERFLOW PROBLEMS
      IF(XK.GE.20.0) GO TO 305
      IF(R.GE.13.0) GO TO 306
      IF(PRO.LE. 1.0E-20) GO TO 307
      PR=PRO*(10.0**(AAC))
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      PREPRO=PRO/.001
      PPPPRO=PR/.001
      PRODBM=10.*ALOG10(PREPRO)
      PREDBM=10.*ALOG10(PPPPRO)
      PREPRR=PR/PRO
      ATNDB=10.0*ALOG10(PREPRR)
C      CALCULATED VARIABLES LOADED IN ARRAYS FOR PRINTOUT
      DBMRG(J)=PRODBM
      DBMARG(J)=PREDBM
      RG(J)=R
      PRORG(J)=PRO
      PRRG(J)=PR
      ATNDRG(J)=ATNDB
  300 CONTINUE
      GO TO 308
  305 WRITE(6,880)
  880 FORMAT(1X,'ATTENTION:  XK.GE.20.....TERMINATING',/)
      GO TO 308
  306 WRITE(6,881)
  881 FORMAT(1X,'ATTENTION:  R.GE. 13...... TERMINATING',/)
      GO TO 308
  307 WRITE(6,882)
  882 FORMAT(1X,' PRO.LE. 1.0E-20.....TERMINATING',/)
  308 JEND=J-1
      DBMARG(1)=-62.
      DBMARG(NRDEL-1)=-132.
      DBMARG(NRDEL)=-132.
C
      WRITE(6,900)
C      900 AND 901 PRINT TABULATED DATA
  900 FORMAT(1X,10X,'RANGE,KM',2X,'UNATTENUATED',12X,'ATTENUATED',21X,
     1'ATTENUATION,',/1X,21X,'RECEIVED',16X,'RECEIVED',27X,'DB',/1X,
     220X,'POWER,WATTS',4X,',IN DBM',3X,'POWER,WATTS',4X,'IN DBM'///)
      DO 301 K=1,JEND
      WRITE(6,901) RG(K),PRORG(K),DBMRG(K),PRRG(K),DBMARG(K),ATNDRG(K)
  901 FORMAT(1X,F16.4,E16.5,F11.2,E13.5,F11.2,F13.2/)
  301 CONTINUE
      WRITE(6,356) RMODEL,IDRPID
C      356 PRINTS GRAPH TITLES
  356 FORMAT('1',20X,'RADAR/COOLING TOWER PLUME ANALYSIS',/1X,19X,
     1'ATTENUATED RECEIVED POWER (DBM)  VS RANGE (KM)',1X,22X,
     2'RADAR MODEL,MODE:',F8.2,/1X,22X,'DROP DISTRIBUTION: KEYSTONE NO.'
     3,I5,//)
      CALL FRPLOT(RG,DBMARG,NRDEL)
  357 CONTINUE
 3006 CONTINUE
      STOP
      END
      SUBROUTINE FRPLOT (X,Y,N)
C
C     PLOTS X(1)......X(N)  VS
C             Y(1)......Y(N)    WITH SYMBOL +
C
      DIMENSION X(N),Y(N),P(99),HO(8),V(8),IP(99)
      DATA B/1H /,S/1H+/
      DO 5  I=1,99
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```
      IP(I)=0
    5 CONTINUE
C
      XL=0.
      XR=X(I)
      YT=Y(1)
      YB=Y(1)
      DO 20  I=2,N
   10 IF  (X(I).GT.XR) XR=X(I)
   20 IF  (Y(I).LT.YT)  YT=Y(I)
      V(1)=YT
      HO(1)=XL
      DO 30  I=2,7
      V(I)=V(I-1)-(YT-YB)/7.0
   30 HO(I)=HO(I-1)+(XR-XL)/7.0
      V(8)=YB
      HO(8)=XR
      WRITE(6,121)
      YTB=49.0/(YT-YB)
      XRL=98.0/(XR-XL)
      KK=0
      DO 90  I=1,50
      DO 40  J=1,99
      P(J)=B
      IPJ=IP(J)
   40 IF(IP(J).NE.0)  P(J)=S
      DO 60  J=1,N
      IF (INT((Y(J)-YB)*YTB+0.5)-50+I)  60,50,60
   50 IXI=INT((X(J)-XL)*XRL+1.5)
      IP(IXI)=1
      P(IXI)=S
   60 CONTINUE
      IF (MOD(I-1,7)) 80,70,80
   70 KK=KK+1
      WRITE(6,131)  V(KK),(P(J),J=1,99)
      GO TO 90
   80 WRITE (6,141)  ((P(J),J=1,99))
   90 CONTINUE
      WRITE (6,151)  HO
      RETURN
  121 FORMAT(16X,1H*,7(13X,1H*)/15X,101(1H-))
  131 FORMAT(E14.4,2H*I,99A1,2HI*)
  141 FORMAT (15X,1HI,99A1,1HI)
  151 FORMAT (15X,101(1H-)/16X,1H*,7(13X,1H*)/9X,8(F9.4,5X))
      ENC
//X.SYSIN DD *
```