# Technical Note 1970-5

# Report on a Weather Radar Study for Aerospace Instrumentation Program Office (ESSI) Electronic Systems Division

J. W. Meyer,
Editor

5 February 1970

Prepared under Electronic Systems Division Contract AF 19(628)-5167 by

**Lincoln Laboratory**
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

# REPORT ON A WEATHER RADAR STUDY
# FOR
# AEROSPACE INSTRUMENTATION PROGRAM OFFICE (ESSI)
# ELECTRONIC SYSTEMS DIVISION

*J. W. MEYER, Editor*

*Division 4*

TECHNICAL NOTE 1970-5

5 FEBRUARY 1970



LEXINGTON MASSACHUSETTS

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, with the support of the Department of the Air Force under Contract AF 19(628)-5167.

## ABSTRACT

Presented here are the conclusions and recommendations of an ad hoc study group which investigated the problems and opportunities of providing improved airborne severe storm reconnaissance with special emphasis on airborne radar detection and surveillance of hurricanes. Study group recommendations are made in terms of what can and should be done in three epochs: by the 1970 hurricane season, by the 1971 hurricane season, and by the 1972 hurricane season. Several options are listed to allow some flexibility in choice of implementation. Discussion of the rationale is also included, and suggestions of desirable improvements in areas other than radar are made. A rudimentary radar hurricane model is presented to aid in the analysis of competing systems, and the implications on radar design of the radar requirements as presented are discussed. Throughout our deliberations we recognized the urgency of implementation of an improved radar and the constraints thereby imposed, but also saw the need of a more pervasive review by a group consisting of members from the government agencies, from the operational units, and from the several scientific and technical disciplines that should be involved in the development of national resources for improved severe storm reconnaissance, analysis, and forecasting.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

## TABLE OF CONTENTS

This study was carried out during November and December 1969 under the general supervision of H. G. Weiss and was coordinated by J. W. Meyer. Study group members are listed below:

R. K. Crane
M. Labitt
J. W. Meyer
C. E. Muehe
C. M. Rader
M. L. Stone
H. G. Weiss

We gratefully acknowledge the assistance of H. P. McCabe in compiling needed data on airborne radar systems.

REPORT ON A WEATHER RADAR STUDY
FOR
AEROSPACE INSTRUMENTATION PROGRAM OFFICE (ESSI)
ELECTRONIC SYSTEMS DIVISION

## I. INTRODUCTION

Hurricane Camille, the most savage hurricane to strike the mainland of the United States, focused national attention on our ability to detect, analyze, track, forecast, and disseminate credible warnings of severe storms. In a Report to the Administrator, Environmental Science Services Administration (ESSA), entitled "Hurricane Camille,"* a survey team described in detail the dreadful saga of this killer storm.

A Navy reconnaissance plane dispatched out of Jacksonville on Thursday morning, 14 August 1969, to investigate a suspicious disturbance, discovered Camille 400 miles south of Miami and 60 miles west of Grand Cayman Island, a depression which grew with remarkable speed to reach storm intensity while Navy 7 was circling the area. Camille moved ashore just east of Bay St. Louis, Mississippi just before midnight Sunday, 17 August, with winds gusting to nearly 200 miles an hour and tides ranging 15 to 30 feet above normal just east of the eye.

From the time of discovery to the point where shore-based radars are able to see the storm, it is the task of airborne reconnaissance to establish the position of the hurricane, measure the lowest sea level pressure, and find the maximum surface winds. To get this information for the National Hurricane Center, it is now necessary for the aircraft to penetrate to the center of the storm. Air Force, Navy, and ESSA Research Flight Facility aircraft carry out this reconnaissance in accordance with the National Hurricane Operations Plan, mutually agreed upon and published by the Sub-Committee on Basic Meteorological Services. The Air Force uses WC-130

---

*"Hurricane Camille, A Report to The Administrator," U. S. Department of Commerce, Environmental Science Services Administration, 12 September 1969.

aircraft (Fig. 1), the Navy, WV-2 (Fig. 2), and the Research Flight Facility uses a DC-6B (Fig. 3). In none of these aircraft have the radar systems used been designed specifically for storm reconnaissance. The Navy plane uses AEW radars (AN/APS-20, AN/APS-45), the Air Force, a weather radar (AN/APN-59), and ESSA, a Collins Model 101 C-band radar for penetration, an APS-20 (smaller antenna than on a WV-2), and a commercial Bendix RDR-1 for range-height indication (RHI) of eye wall clouds.

## II. PROBLEMS ENCOUNTERED IN CAMILLE RECONNAISSANCE

Paradoxically, reconnaissance problems encountered with Camille were not directly related to radar. A summary of reconnaissance on Camille is contained in Fig. 4. An Air Force reconnaissance aircraft reported central pressure in the eye taken with a dropsonde which was accurate but such a low pressure that it was difficult to believe. Communications difficulties made it impossible to ask for a corroborative run before a warning had to be issued by the National Hurricane Center. A navigation error in connection with a Navy fix on the storm's location placed the eye to the east of the actual path. This occurred in a region where the forecasters expected a recurvature in its path so that the fix could not be discounted. This increased the uncertainty regarding the forecast of Camille's probable landfall. Another factor was that too few planes were available to provide continuous and/or complementary coverage at critical times during Camille's life. Early in this period one mission was aborted because of radar failure.

This experience with Camille points up the importance of an integrated approach to the airborne reconnaissance system as a whole and its interface with the many facets of our weather surveillance and reporting system on the ground.

## III. ESSA SURVEY TEAM RECOMMENDATIONS

The ESSA survey team which examined the Camille activities recommended that highest priority be given to:

"1. Public education and community preparedness programs.

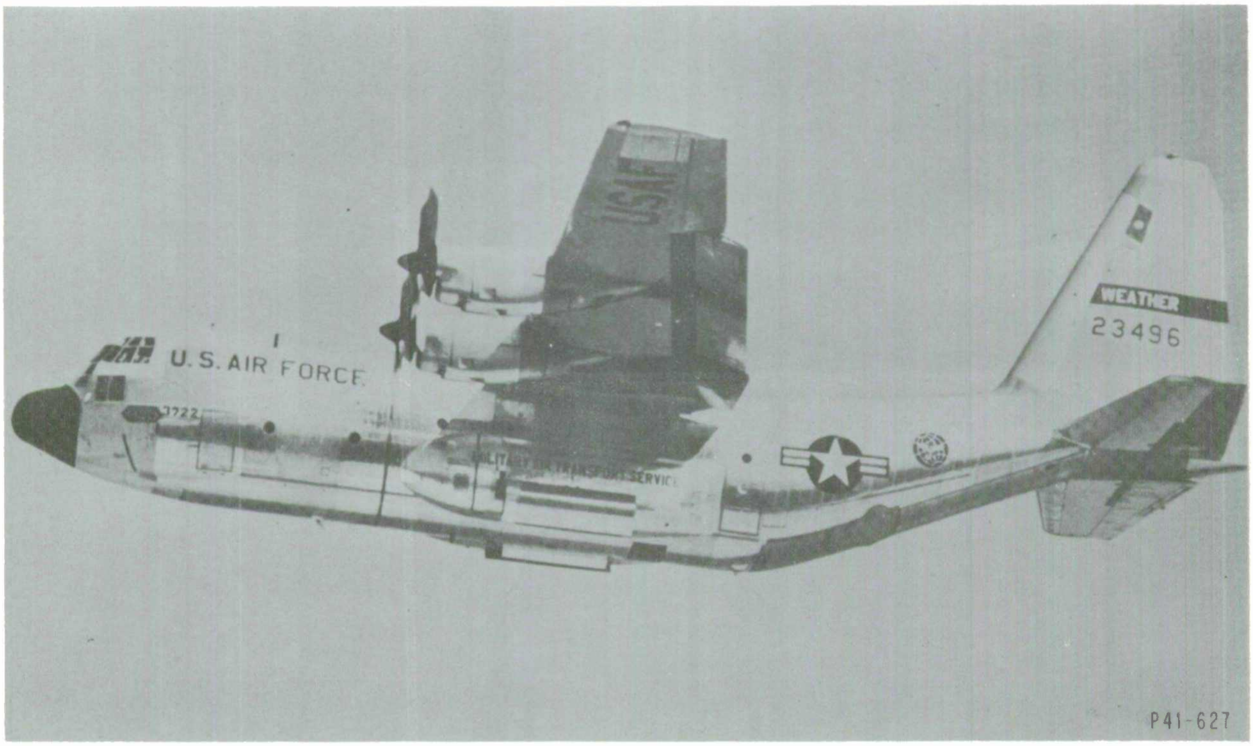



Fig. 1. Air Force WC-130 weather reconnaissance aircraft. After R. H. Simpson, "The Tracking and Observation of Hurricanes," Am. Soc. for Oceanog. Pub. 1, Hurricane Symposium, 10-11 October 1966, Houston, Texas.

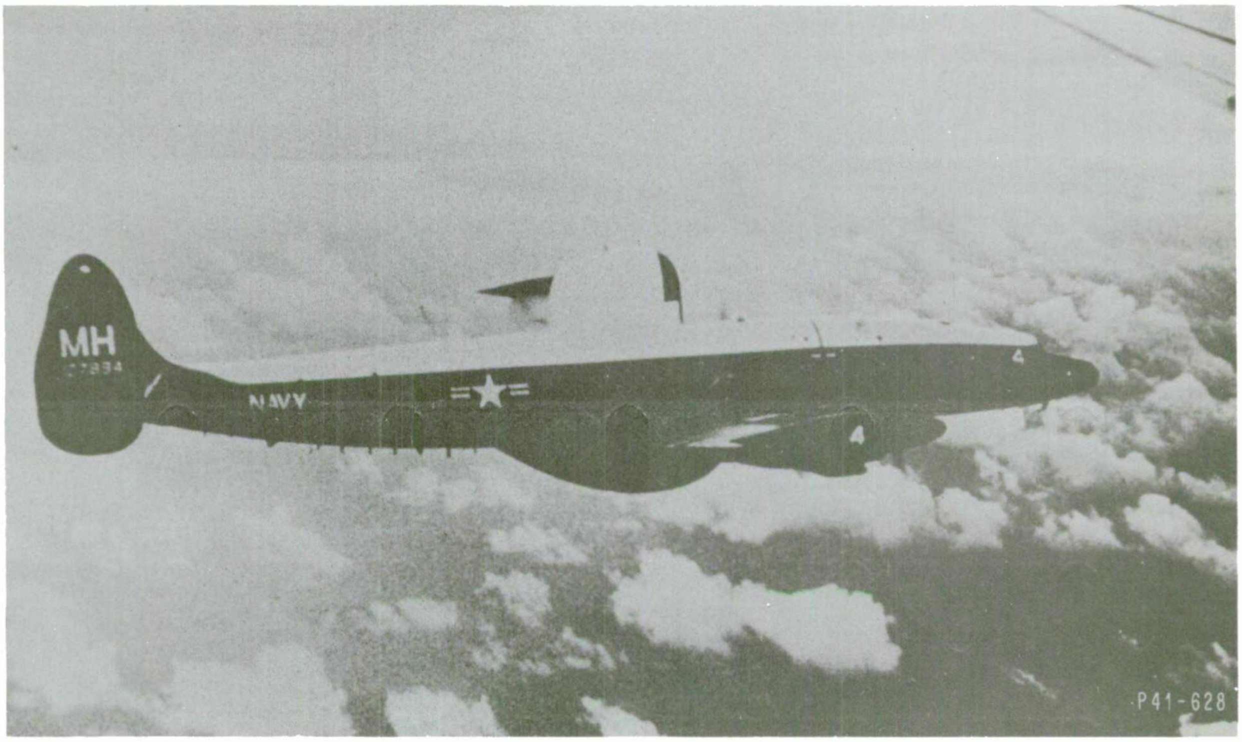



Fig. 2. Navy WV-2 weather reconnaissance aircraft. After R. H. Simpson, loc. cit.


Fig. 3. Weather Bureau DC-6 weather research aircraft. After R. H. Simpson, loc. cit.

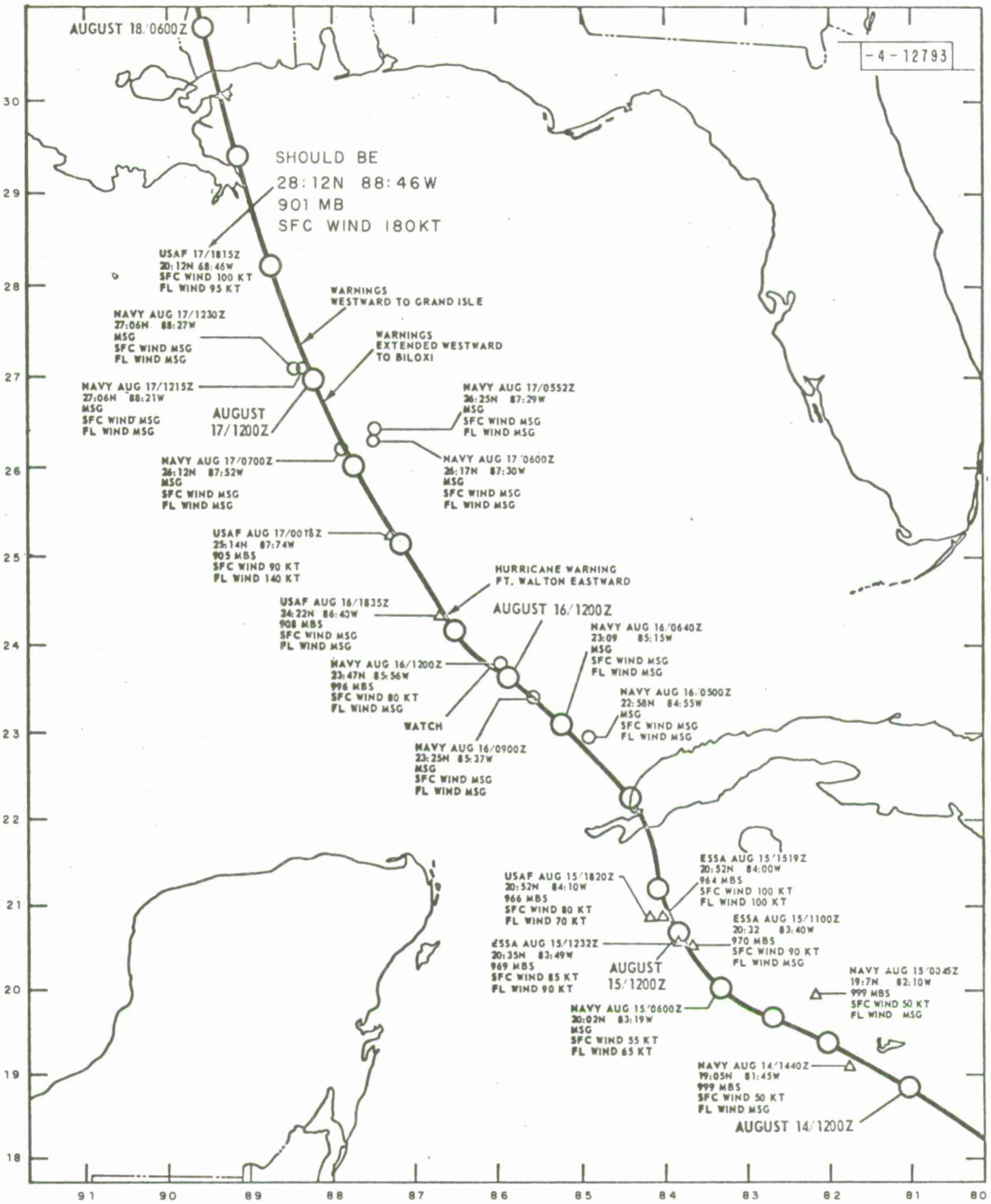



Fig. 4. Summary of aircraft reconnaissance of Hurricane Camille. From "Hurricane Camille, A Report to The Administrator," U. S. Department of Commerce, Environmental Science Services Administration, 12 September 1969.

2. Improved aircraft reconnaissance.*
3. Safe quarters and reliable power and communications facilities.
4. Forecasting research and techniques development based upon new technologies be accelerated as we approach a minimum standard of preparedness and public awareness of the consequences of a failure to respond to hurricane warnings."

Specific recommendations of a more technical nature were also made which included:

Develop standardized instrument package for operational and research and development type reconnaissance aircraft with careful coordination among the three services in order to facilitate information flow and to make all data more useful for research purposes.

Make a comparative study of existing communications systems to determine the best system for use in hurricane emergencies which can improve transmission of reconnaissance information on the position and intensities of hurricanes to the National Hurricane Center.

Additionally, the survey team observed that the Navy needs better aircraft, the Air Force needs better radar, and the ESSA Research Flight Facility could use both a better aircraft and better radars.

## IV. AIR FORCE PROJECT "SEEK STORM"

On 4 November 1969, representatives of the Aerospace Instrumentation Program Office, of the Electronic Systems Division, visited the Laboratory to discuss what might be done to provide improved radar performance on the Air Weather Service's aircraft (WC-130, WC-135). Specifically, the objective of Project Seek Storm is to develop advanced weather radar/radars

---

*Action be undertaken leading to improvement in the aircraft and sensory equipment used in aerial reconnaissance. ("A special analysis of hurricane reconnaissance is being undertaken by the Federal Coordinator for Meteorological Services and separate recommendations on this phase of the hurricane tracking problem will be made.") See U.S. Department of Commerce Publication FCM 69-1 dated 26 September 1969.

for Air Weather Service aircraft. A development plan of about two years' duration was wanted to devise improved WC-130 radars for hurricane surveillance and penetration.

As presented to us, the Seek Storm task is to design, construct, and test an experimental model of a radar system that will:

1. Locate precipitation areas.
2. Display storm eyes 5 nautical miles in diameter at 200 nautical miles range.*
3. Function in both light and heavy precipitation.
4. Provide five-level contour display of echo levels.
5. Provide range up to 200 n. mi. (30, 100, and 200 n. mi. displays).
6. Range accuracy < 2 n. mi., azimuth accuracy $1^{\circ}$.

Constraints:

1. System must be compatible in size and weight with WC-130 and WC-135 aircraft.
2. Airframe modifications must enable it to continue to withstand forces encountered in approaching and penetrating severe tropical storms.

Desired Outputs:

1. Recommendations on radar system/systems parameters and specifications.
2. Devise radar storm model for radar system performance analysis.
3. Detect requirements that cannot be met. If any are found,
4. Suggest alternate design directions which will lead to the closest realization of those requirements that cannot be met.

At this meeting we agreed to carry out an intensive study of the problem for about six weeks, with the objective of defining both a short-term and a long-term program in airborne weather radar research, development, and test.

---

*This is characterized as a first priority requirement.

V. AREAS OF CONTACT FOR BACKGROUND

The study group was well balanced in that it included staff experienced in physical meteorology, weather radar, airborne AEW MTI radar, radar systems, data processing, and communications systems. To broaden this background further, we felt it important to tap the experience of the members of M.I.T.'s Department of Meteorology (see Appendix I). Contacts were also made at the University of Miami, the USAF Air Weather Service, the Aeronautical Systems Division, ESSA Weather Bureau, the Naval Air Systems Command, and the airframe manufacturer (C-130), Lockheed Georgia Company.

We used these contacts to establish rapport with key agency personnel, to acquire background on innovations in weather sensing, forecasting, and modification, to evaluate the USAF Requirements Action Directive, and to provide in-depth background for our recommendations.

VI. ATLANTIC HURRICANE RECONNAISSANCE

The organization, authority and responsibility for Atlantic, Caribbean, and Gulf of Mexico hurricane reconnaissance is shown in Fig. 5. The National Hurricane Center analyzes reconnaissance data, makes forecasts, and requests reconnaissance flights through CARCAH (Chief Aerial Reconnaissance Coordination, Atlantic Hurricanes) by Air Force, Navy, or Research Flight Facility Aircraft. Because no military flights within 30 miles of the mainland of Cuba are allowed, aircraft from the Research Flight Facility do the Cuban overflight missions when necessary.

The National Hurricane Operations Plan dated April 1969 points out that the Air Force and Navy share reconnaissance responsibility equally. They are to provide fixes and investigative flights, the Air Force at 700 millibars (10K ft) and above and the Navy at 700 millibars and below. Flight safety regulations preclude Navy aircraft (WV-2) penetrating the storm if: (1) diameter of storm eye is less than 15 nautical miles, (2) AN/APS-20 radar inoperative, (3) observed or forecast surface winds in excess of 120 knots. In addition, low-level penetrations are not permitted during darkness.

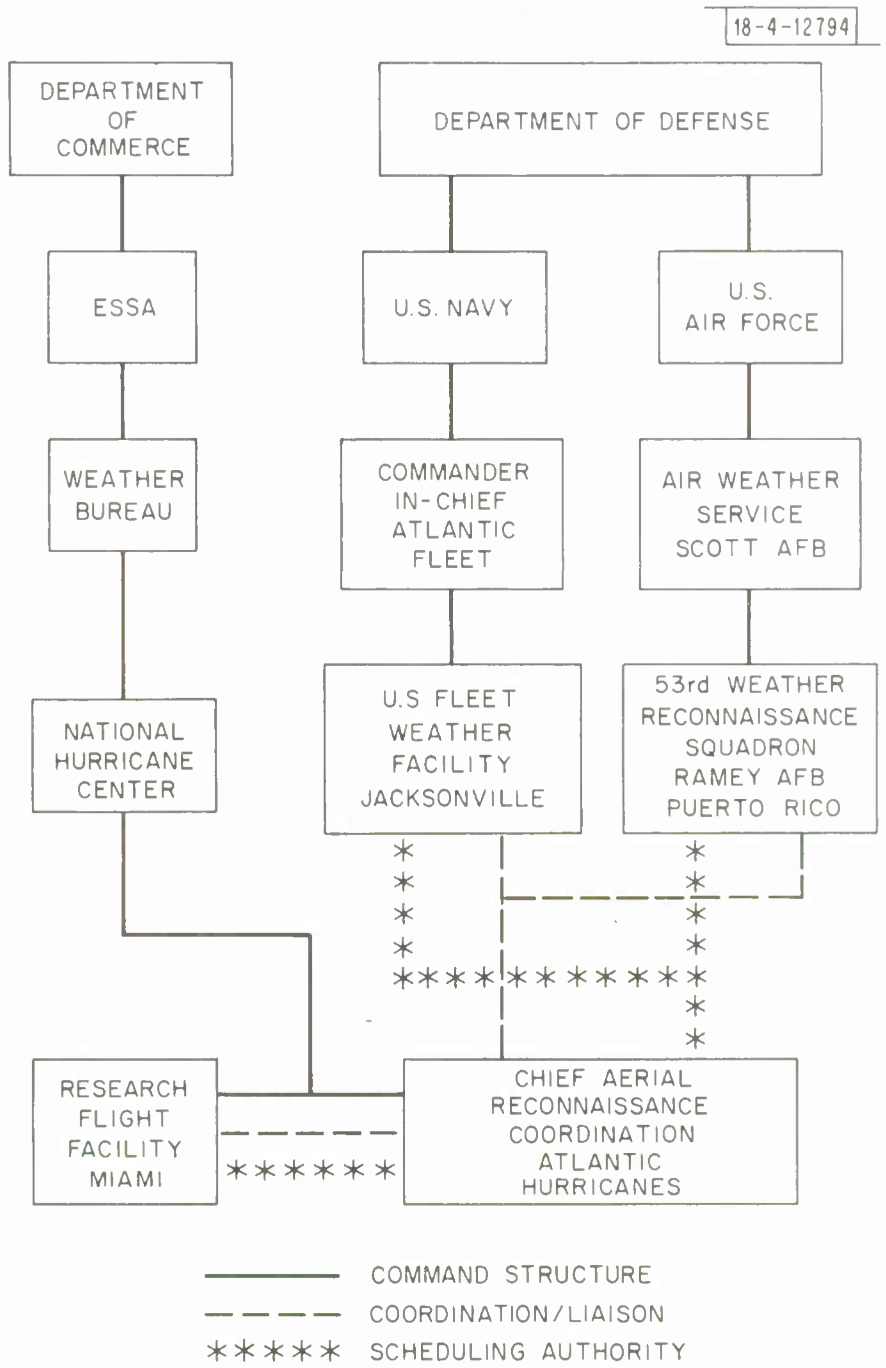



Fig. 5. Abridged organization chart for Atlantic, Caribbean, and Gulf of Mexico hurricane and tropical cyclone investigations: cooperating agencies.

As it now reads, the operations plan calls for the following reconnaissance data:

A. Fixes on Storm Center:

1. Observe as soon as possible, by whatever means possible upon entering cyclonic circulation:
   a. Size, shape, orientation of eye
2. Priority of eye fix methods:
   a. Cloud eye: from within eye, visual or radar
   b. Wind eye: spot winds accurately
   c. Pressure eye: locate position of lowest surface pressure using prescribed flight pattern, and dropsonde from 500-millibar altitude ($\sim$18K ft)
   d. Radar eye: obtained from radar coverage from outside eye
3. Classification of eye position fix accuracy:
   a. Less than 10 miles -- excellent
   b. Less than 20 miles -- good
   c. Less than 40 miles -- fair
4. Frequency of center fixes:
   a. At 6-hour intervals
   b. At times as close as possible to:
      1. 1200 Z
      2. 1800 Z
      3. 0000 Z
      4. 0600 Z

B. Wind Profile:

1. Measure horizontal wind speed profile from about 100 miles radius to the storm center, at 700-millibar level, or lowest safe level.

C. Cumulonimbus "Blow-offs":

1. Observe direction of "blow-offs" from tops of cumulonimbus clouds--to be reported by flights operating below 25,000 ft.

2. This data needed east of 60°W longitude to aid in determining ing upper tropospheric winds.

D. Peripheral Data:

1. As time and operational conditions permit, observe:

    a. At 500-millibar altitude or slightly above:

        1. Winds

        2. Temperatures

        3. Heights of pressure surfaces outward to a radius of 500 miles from the storm center.

From the requirements as outlined in the operations plan, it is clear that penetration by the aircraft of the storm center is the only way now open to obtaining the necessary reconnaissance data.

In summary, the following are the primary reconnaissance parameters:

1. Location of storm center
2. Accurate sea level pressure at storm center
3. Flight level winds

Reconnaissance parameters for the 1970 season will also include:

1. D values*
2. Cloud height in eye wall

from which operation requirements of the radar are:

1. Detect at long range precipitation motion and form
2. Aid in storm penetration
3. Measure cloud height

(There is no way of implementing the cloud height measurement in the WC-130 without some structural modification to the aircraft. Rain-rate information is not now used in storm track forecasting nor is it accurately sensed with a C- or X-band radar because of our inability to quantitatively allow for rain attenuation in those bands. The primary use of the radar in

---

*D value: Pressure height difference exhibited between a standard atmosphere at flight level and that measured. Operationally it is determined by subtracting the indicated pressure altitude from the true altitude as measured with a radar and/or corrected pressure altimeter.

the near term therefore is to aid the aircraft in penetrating the storm for the required non-radar measurements. For these reasons, we sought an immediate solution to the problem of safely penetrating and exiting a well-developed, severe hurricane.)

## VII. MAC/AWS/ASD RECOMMENDATIONS

The Air Weather Service with the assistance of the Aeronautical Systems Division suggests that the following improvements might be accomplished in time for the 1970 hurricane season:

Modify the APN-59 radars now in the WC-130 aircraft as follows:

1. Increase transmitter peak power by about 3 dB
2. Increase receiver sensitivity by about 4 dB
3. Mount 45-inch antenna with pencil beam (4 dB better)
4. Add two 10-inch PPI (off center sweep) displays

Install X-band weather radar for RHI cloud height data in new tail cone radome. Suggested surplus APS-42. (ESSA uses Bendix RDR-1 in tail radome on their DC-6B).

## VIII. A NEW HURRICANE RECONNAISSANCE FLIGHT PLAN FOR 1970

The National Hurricane Center is recommending a new series of standard reconnaissance tracks for aircraft making hurricane investigations. The investigation of a fully organized storm anticipates that the aircraft will be able to remain in the area of the storm for two successive fixes six hours apart. The storm is to be located using a long range S-band radar and with the help of probable location coordinates for the center from the National Hurricane Center. The Flight plan as shown in Fig. 6 indicates that penetration is begun from the direction of the left rear quadrant, the track traversing the eye and exiting through the right front quadrant. It is in the right front quadrant that the greatest rainfall and turbulence is encountered. A second transit of the eye is made from the left front to the right rear quadrant about 90 minutes after the first fix of the eye center was made. A computation of the storm movement over this period can then be made. The surveillance track laid out in advance of the storm movement is to be flown at an altitude permitting measurement of the sea surface temperature. When

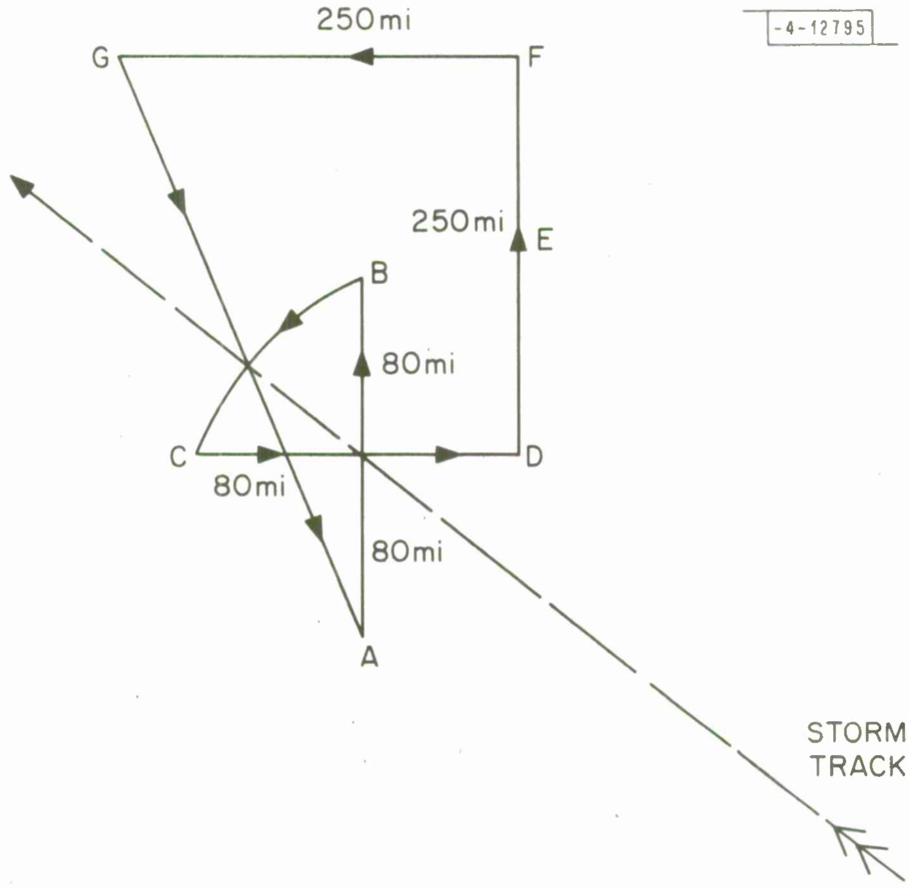



Fig. 6. Reconnaissance flight plan for 1970 as proposed by the National Hurricane Center.

flying this track, the pilot will probably have to depend heavily upon his radar to locate the eye and to navigate the required traverses of it.

For the regenerating or decaying tropical hurricane, other tracks have been recommended, viz., Plan C1 which calls for the fixing of the pressure center, the determination of a minimum surface pressure and a reconnaissance of the right front quadrant at 1500 feet altitude, 300 nautical miles in advance of the center, and Plan C2 which calls for a radial transit from the vortex into or out of the eye in order to obtain a profile of equivalent potential temperatures in addition to the location of the pressure center and the determination of the minimum surface pressure.

A standard flight track recommended for investigative flights involves the determination of the pressure center if it exists, the maximum winds, plus the reporting of wind and pressure profiles in the direction of maximum pressure gradient. The track to be flown will be defined by the National Hurricane Center when the flight is dispatched.

These tracks involve significant changes in the National Hurricane Operations Plan as it now reads. The suggestions are now under review, and as yet are not official, but are valuable ingredients for the planning of advanced weather sensory systems. This recommendation indicates what is desired by the meteorologist to aid him in collecting the data needed for accurate analysis, prediction, and forecast.

## IX. RADAR DETECTION OF RAINFALL

Weather radar workers frequently compare systems in terms of a minimum detectable precipitation reflectivity factor, Z, with an equation of the following form:

$$Z = C \frac{P_{min} \lambda^2 r^2}{P_t G h},$$

or

$$Z_{100} = C^1 \frac{P_{min} \lambda^2 \theta \varphi}{P_t \tau}, \text{ at 100 miles range,}$$

TABLE 1

A COMPARISON OF RAINFALL DETECTION BY
SEVERAL RADARS IN THE ABSENCE OF PATH ATTENUATION

| Radar | $\lambda$ (cm) | $\tau$ ($\mu$ sec) | $P_t$ (Kw) | $P_{min}$ (w) | $\theta^o/\varphi^o$ | $Z_{100}$ $\frac{mm^6}{m^3}$ | $R_{100}$ mm/hr* |
|---|---|---|---|---|---|---|---|
| UM-10 | 10.0 | 2.0 | 726 | $2.5 \times 10^{-14}$ | $3^o/2.7^o$ | 11 | 0.09 |
| APS-20 PPI | 10.4 | 2.0 | 2000 | $2.5 \times 10^{-14}$ | $1.5^o/6.2^o$ | 5 | 0.05 |
| APS-82 | 10.0 | 2.0 | 1000 | $2.5 \times 10^{-14}$ | $1.5^o/6^o$ | 2.5 | 0.03 |
| MPS-4 | 4.6 | 1.3 | 150 | $3.2 \times 10^{-14}$ | $4^o/0.8^o$ | 9 | 0.08 |
| APS-45 RHI | 3.2 | 1.8 | 450 | $5 \times 10^{-14}$ | $3^o/1^o$ | 1.5 | 0.02 |
| APS-103 RHI | 3.2 | 2.0 | 1000 | $5 \times 10^{-14}$ | $3.1^o/1.2^o$ | 0.9 | 0.02 |
| APN-59 | 3.2 | 2.0 | 58 | $4 \times 10^{-14}$ | $3^o/5^o$ | 36.1 | 0.22 |

*Note: The empirical relation between R and Z is not known to an accuracy of R values better than a factor of two. In the equation $Z = AR^B$, A and B can vary widely and still give this accuracy. See curves on Fig. 9.

which include the following assumptions:

1. The scatters fill the radar resolution element as defined by the antenna beam and pulse width.
2. Propagation path attenuation not included.
3. Individual particle scattering cross section $\sigma \propto D^6/\lambda^4$ (Rayleigh scattering)

C and $C^1$ collect constant terms

Z = minimum detectable precipitation reflectivity at distance r

D = diameter of drop

$P_{min}$ = minimum detectable signal power

$\lambda$ = wavelength

r = range

$P_t$ = peak transmitter power

G = antenna gain

$\theta$ = horizontal beamwidth

$\varphi$ = vertical beamwidth

$\tau$ = pulse width

h = range resolution $c\tau/2$

or if one wished to compare the performance of two weather radars operating at the same wavelength under the above assumptions,

$$\frac{Z_1}{Z_2} = \frac{\tau_2}{\tau_1} \cdot \frac{P_{min\ 1}}{P_{min\ 2}} \cdot \frac{P_{t2}}{P_{t1}} \cdot \frac{(\theta\ \varphi)_1}{(\theta\ \varphi)_2} .$$

Because attenuation is not included in the above formulae, and because propagation effects are wavelength dependent, radars operating at widely differing wavelengths should not be compared using this ratio. This formula is useful, however, for comparing radars with which we have experience with those for which we have little empirical data. Complete analysis requires a storm model from which we can compute scattering cross section and propagation loss.

Several radars are compared in Table 1 on the basis of rainfall detectability alone, with no allowance made for propagation loss.

## X. A HURRICANE MODEL FOR WEATHER RADAR EVALUATION

Detailed meteorological models of hurricane structure are not available. Only a relatively small number of hurricanes have been measured in sufficient detail to get a general picture of the wind, temperature, water vapor and hydrometer distribution in time and space. From the few hurricane measurements available,*† only a general physical description of a "typical" hurricane can be given. As seen on a radar PPI display (Fig. 7), a hurricane would consist of several rain band echoes that spiral into a central, generally circular, echo-free region. The echo-free region or radar eye usually coincides with the calm central pressure eye of the hurricane.

The rain cells at the edge of the eye or the "wall clouds" are in the region having the highest horizontal and vertical wind speed. These clouds are the heavy rain producers. Rainfall rates in the large cells typically exceed 150 mm/hr. Weather radar PPI photographs indicate that the rain area associated with the eye wall clouds occupies a ring of the order of 20 km thick. The rain bands spiral into this ring from distances around 150 km from the center of the eye. The spiral bands are typically about 30 km wide. We must emphasize that these areal estimates might vary widely from storm to storm. In some hurricanes, for example, the eye clouds do not form a complete ring, in others double rings are found, and in others the spiral structure appears to be smeared out in space.

The usual radar PPI photograph available in the literature does not present quantitative information about the spatial distribution of rainfall intensity. A rainfall intensity distribution can only be inferred from the general meteorological descriptions that are available. Rain rates in excess of 150 mm/hr can be expected in one, or at most a few, distinct cells in the eye wall region. These high rain rate cell cores are estimated to be the

---

* Malkus, J. S., Large Scale Interactions in the Sea, Vol. I, N. M. Hill, Ed. (Interscience Wiley, New York, 1962).

† LaSeur, N. E., "On the Description and Understanding of Hurricane Structure," Proc. Hurricane Symposium, Am. Soc. for Oceanography, Pub. No. 1, 71-81 (1966).

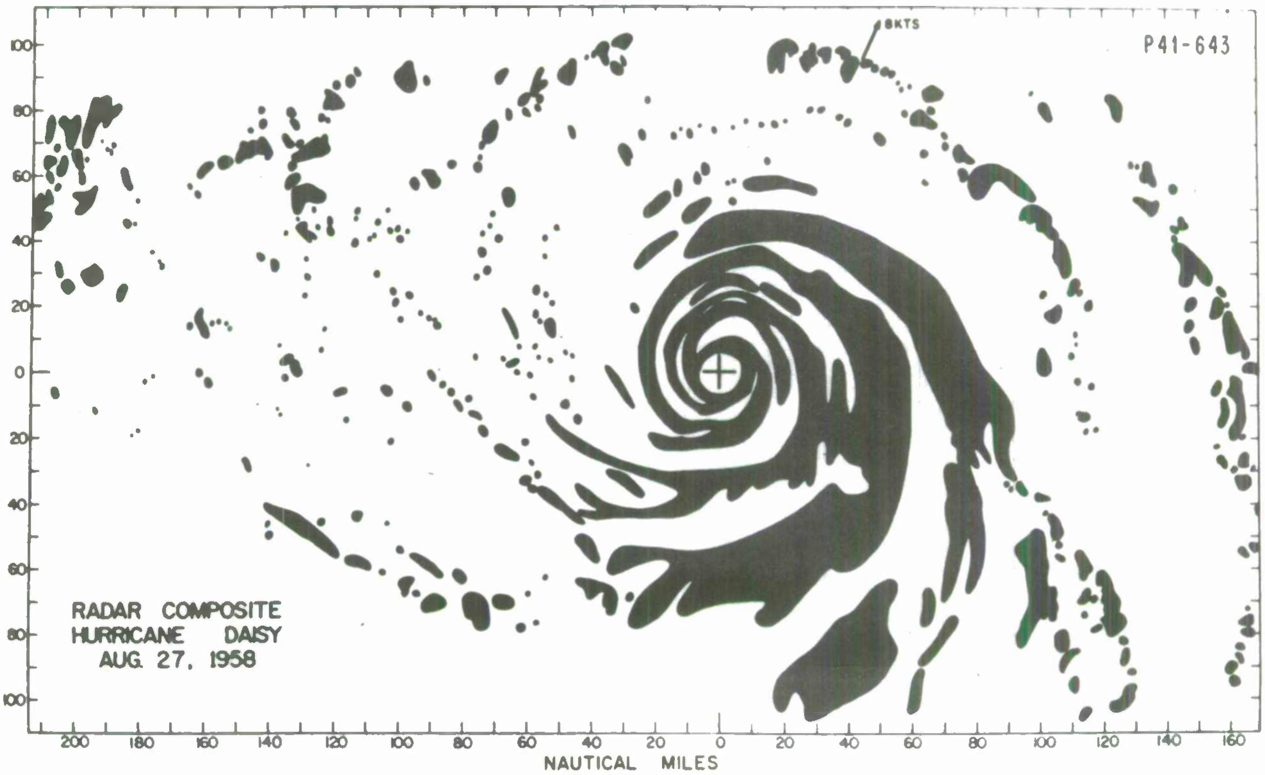



Fig. 7. Composite (from aircraft radar flights) radar picture of cloud echoes in Hurricane Daisy on 27 August 1958. Note the circular wall cloud surrounded by spiral "rainbands." After J. Simpson, "Hurricane Modification Experiments," Hurricane Symposium, 10-11 October 1966, loc. cit.

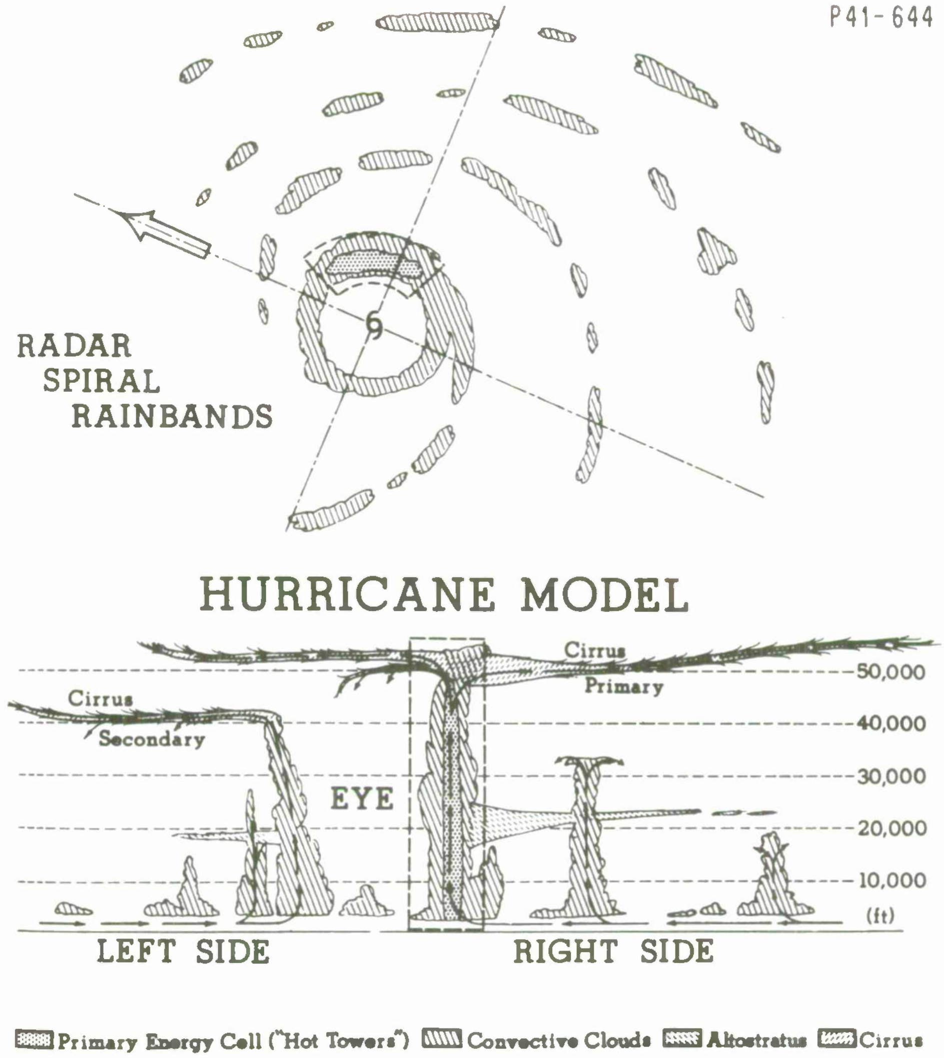



Fig. 8. Hurricane model, derived from ten years of hurricane research flights. Above, schematic radar picture (compare with Fig. 7). Arrow denotes direction of storm motion, box shows typical "chimney cloud" region. Below, vertical cross section along line normal to storm's motion. Note chimney cloud (boxed) on right side of central eye. After J. Simpson, "Hurricane Modification Experiments," loc. cit.

order of 5 to 10 km wide and 10 to 15 km high. Rainfall rates in regions just outside the intense cells are expected to be the order of 10 mm/hr, thence decreasing to 2 mm/hr at the edges. Rain rates in the outer spiral bands are expected to be the order of several mm/hr, with the possibility of small convective rain cells imbedded in the broad area of low rain intensity. These small convective cells, only a kilometer or so across, have rainfall rates approximating 50 mm/hr in their cores. Rain in the low rainfall intensity areas usually originates from snow which turns to rain at the melting level, producing the so-called radar "bright band" at that level. The radar cross section of melting hydrometeorites in the thin bright band is usually 5 to 10 dB higher than that of the droplets which emerge beneath it.

In summary, our radar model of a hurricane consists of a spiral band structure with band breadths about 30 km and rain rates therein the order of 2 mm/hr. Within these bands, small convective cells (1 to 2 km diameter) are found which have rain rates the order of 50 mm/hr. The spiral band structure extends 150 km from the center of the storm system, an echo-free eye, 10 to 20 km diameter, bounded by a wall containing several large, intense rain cells. These rain cells can have rain rates in excess of 150 mm/hr, over diameters of the order of 5 km. This hurricane model is based principally on inference from existing meteorological models and not on actual measurements. The only available radar measurements are qualitative and do not provide a description of the meso-scale rain structure. Observations of real hurricanes might vary appreciably from this model and from each other (see Fig. 8).

In designing an airborne weather radar, extremes of rainfall are of special interest: (1) the minimum rainfall rate expected, so that the required radar sensitivity can be established; (2) the area occupied by the eye wall cells and their maximum expected rainfall intensity so that path attenuation may be calculated. We set this minimum rate, somewhat arbitrarily, at 0.1 mm/hr. The maximum rainfall intensity is assumed to be 150 mm/hr in a cell or bandwidth of 10 km.

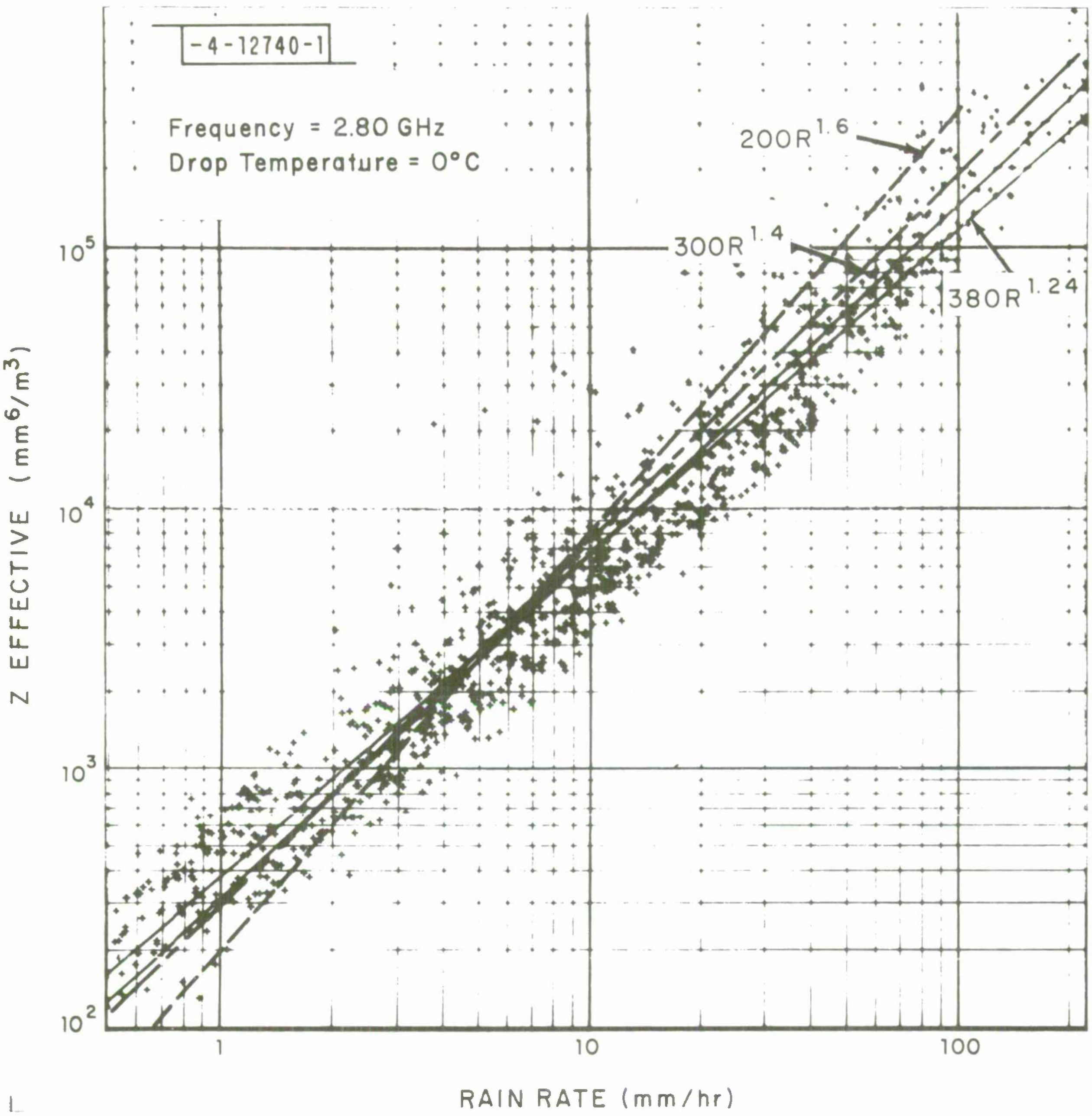



Fig. 9. Backscatter cross section as a function of rain rate computed from drop size distributions as measured in Miami.

The physical model of hurricane precipitation specified above can be converted into radar terms as follows. The radar cross section per unit volume for an ensemble of scatterers which are small compared with a wavelength is given by the Rayleigh scattering law,*

$$\beta = \frac{\pi^5}{\lambda^4} \, |K|^2 \, Z \times 10^{-10} \quad m^2/m^3 ,$$

where $\lambda$ is the wavelength in cm, K is a parameter that depends upon the index of refraction of the water in the raindrop, and Z is the sum of the sixth power of the drop diameters for all the raindrops in a cubic meter (measured in $mm^6/m^3$). For frequencies in the bands S to X, $K \sim 0.95$. For frequencies at X-band and lower, the backscatter cross section is adequately estimated by the above equation. The backscatter cross section depends primarily upon the drop-size distribution. The results of computations made using drop-distributions measured in Miami are given in Fig. 9. The best straight line fit to data is given by

$$Z = 380 \, R^{1.24} \quad mm^6/m^3 ,$$

with an rms error of 60 percent, where R is rain rate in mm/hr. The standard assumption of

$$Z = 200 \, R^{1.6}$$

also fits the data with a slightly higher rms error.

The attenuation due to rain is an important factor in weather radar design. The attenuation vs frequency curves for rain rates typical of the eye wall cores and rain band convective cell cores are given in Fig. 10. From this figure, it is evident that significant attenuation can occur for all frequencies above 5 GHz. The two-way attenuation through an eye wall rain cell would be about 150 dB at X-band (9.35 GHz).

---

* Crane, R. K., "Microwave Scattering Parameters for New England Rain," Technical Report 426, Lincoln Laboratory, M.I.T. (30 October 1966), DDC AD-647798.

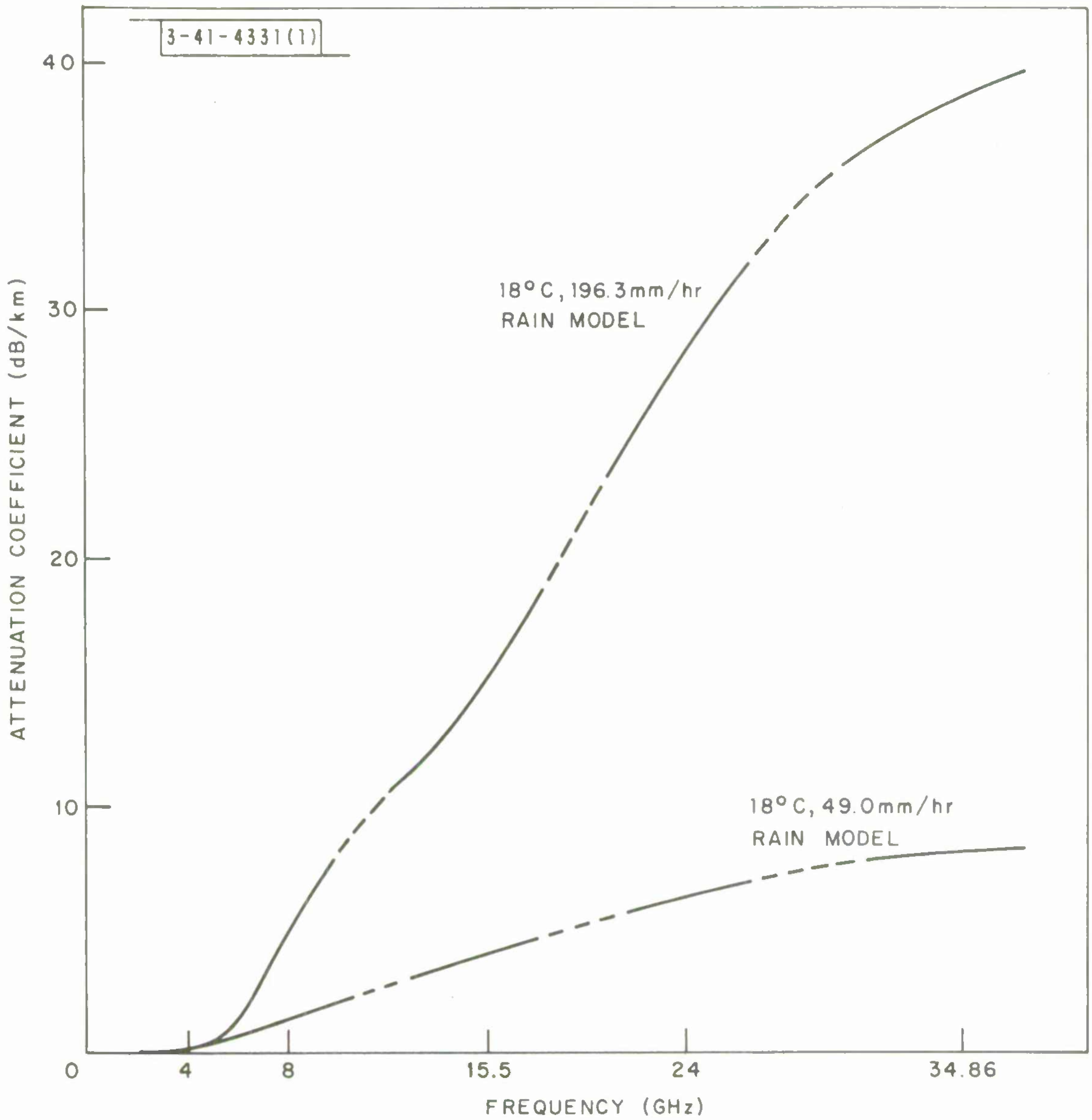



Fig. 10. Attenuation coefficient vs frequency for two different rain intensities.

The attenuation coefficient at X-band for drop-size distributions measured in Miami is shown in Fig. 11. The best straight line fit to the data is given by

$$A = 0.01 R^{1.12} \text{ dB/km}$$

At several frequencies, a table of best fit coefficients in $A = \alpha R^{\gamma}$ follows:

| Frequency GHz | $\alpha$ | $\gamma$ | RMS error |
|---|---|---|---|
| 2.80 | .000407 | 1.00 | 9% |
| 6.00 | .00342 | 1.17 | |
| 8.00 | .00677 | 1.12 | 29% |
| 9.35 | .0104 | 1.12 | 27% |
| 16.00* | .042 | 1.11 | |

Using these data, the attenuation can be approximated by

$$A = \alpha R^{1.1}$$

where $\alpha$ is given in Fig. 10.

The hurricane model gives a physical description of a "typical" hurricane, expected extreme values and the statistical relationships between the radar cross section per unit volume and rain rate and between the attenuation coefficient and rain rate -- parameters important to the design of incoherent weather radars. In the design of a coherent radar system to provide wind measurements using Doppler techniques, we need information about the wind shear and turbulence which broadens the Doppler spectrum. Unfortunately, data on which to base Doppler broadening estimates are not now available.

A final parameter required for the design of an airborne weather radar system for over-water use is the intensity of the sea clutter return. Radar reflections from the sea at the same range as the storm may mask the rain return. Return from the very rough seas obtaining in hurricane winds may be avoided by flying low so that the radar horizon is close to the aircraft.

---

* Using Laws and Parsons model data.

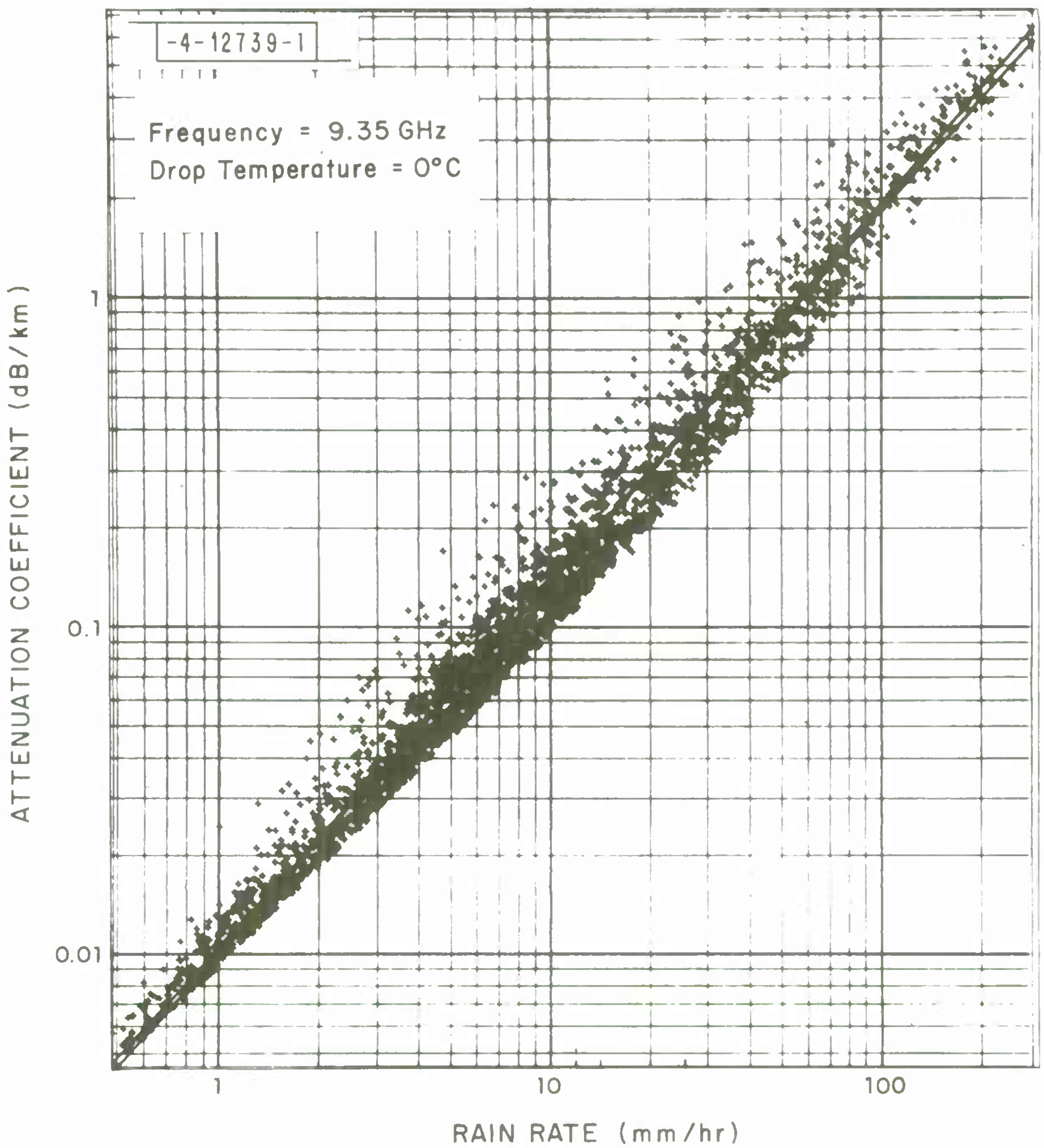



Fig. 11. Attenuation coefficient as a function of rain rate computed from drop size distributions as measured in Miami.

Then the rain echoes are beyond the sea-clutter return. In some situations, antennas with narrow elevation beamwidths discriminate against sea clutter.

The estimation of the diffuse scattering due to the sea at low incidence angles relative to the local horizontal at the point of reflection is a difficult theoretical problem. Estimations are generally based upon comparisons with available measured data. The measurements that are available have not been made for the extremely high sea states encountered in hurricanes.

## XI. TIME CONTEXT OF RECOMMENDATIONS

We identified three working time frames for our recommendations of system improvements: immediate, near term, and long term.

In the immediate context we considered what might be done to improve hurricane reconnaissance in time for the 1970 hurricane season, i.e., about 1 July 1970. This short period would preclude airframe modifications of a nature that would require design and extensive aerodynamic testing. Moreover, only existing equipment with which operational experience had been acquired should be considered. It is also important that modifications accomplished immediately not be drastically undone by modifications proposed for the near or long term.

A reasonable context for the near term would be in time for the 1971 hurricane season, 1 July 1971.

For the long term, the goal would be to have a prototype system installed and flight-tested in an aircraft in time for experiments and tests during the 1972 hurricane season.

## XII. AN IMPROVED HURRICANE PENETRATION AID RADAR FOR THE WC-130

The best penetration aid radar is one that is able to "see through" the storm well enough to display the eye from the outside, which means that the radar must penetrate some of the intense rain bands located adjacent to the eye. From the discussion in the preceding section, we see that the rain bands in the eye wall have such heavy precipitation that they are nearly opaque at X-band wavelengths. We note also that as we go to longer wavelengths the rain bands rapidly become transparent (see Figs. 10, 12). As

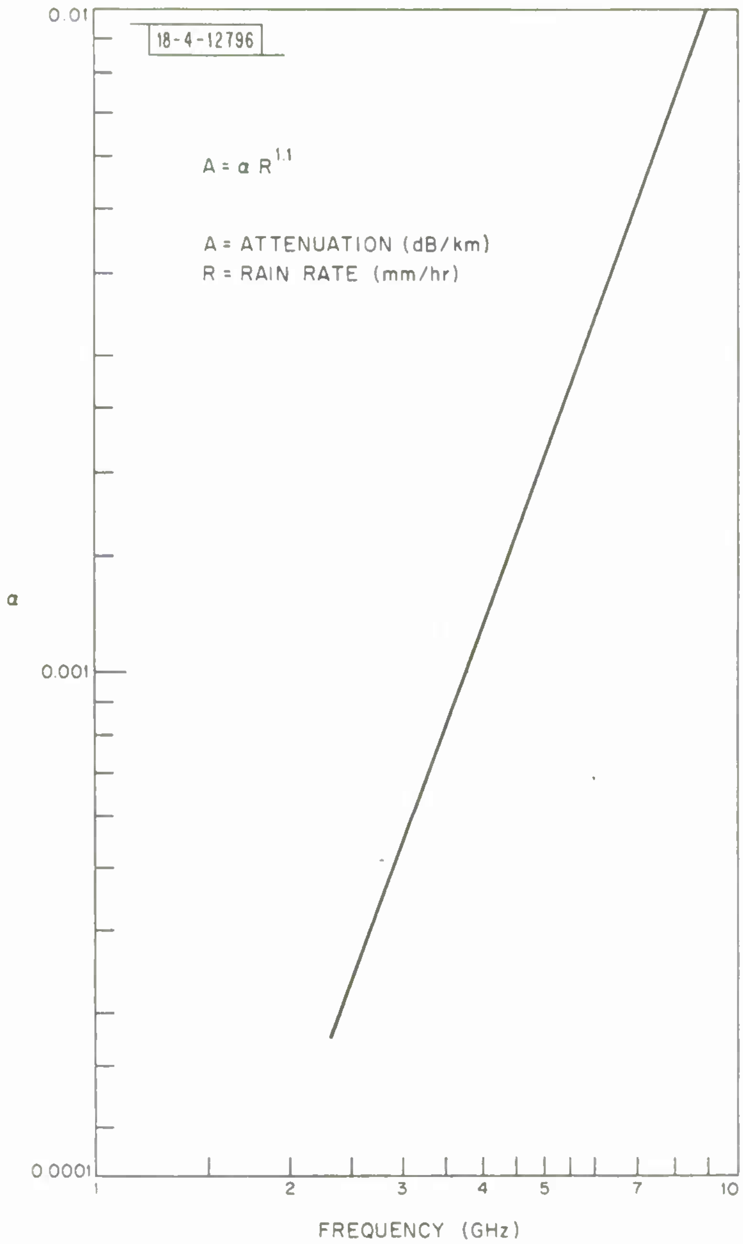



Fig. 12. Coefficient $\alpha$ as a function of frequency.

can be seen in Fig. 13, the APS-20 radar on the Navy's WV-2 aircraft does a very good job of displaying the structure of hurricane from well outside the eye. Unfortunately, the size of the radome on the WC-130 limits the size of the antenna that it can contain to between 30 and 45 inches diameter. With this fixed aperture, as we lower the frequency to improve radar penetration, we increase the radar's beamwidth and hence the amount of rainfall in its resolution volume. If, however, the transparency increases fast enough compared to the increased beamwidth, one would get improved performance as a radar hurricane penetration aid for the aircraft. A number of candidates as a quick fix radar are listed in Table 2.

In the calculation that follows, the modified APN-59 (9 to 11 dB improvement) X-band radar is compared with a modern C-band weather radar, the RCA AVQ-30C, which has been developed for installation in "jumbo jet" commercial aircraft. While this specific radar seems well suited for quick fix purposes, other radars with similar characteristics can be substituted.

Two different weather models were used in these calculations of the minimum detectable precipitation reflectivity, $Z_{100}$, and the minimum detectable rainfall, $R_{100}$, at a range of 100 miles. Expressions for these factors which include attenuation in rain are:

$$Z_{100} = \frac{8\pi P_r \, r^3 \lambda^2 \varphi^2 \theta}{P_t c \tau h \pi^5 \, |K|^2} \quad \exp\left[-\beta \left(\frac{\lambda_o}{\lambda}\right)^{5/2}\right] \int_o^{2r} R^{1.1}(s)\, ds \quad \frac{mm^6}{m^3}$$

$$R_{100} = (Z_{100}/200)^{\frac{1}{1.6}} \qquad mm/hr$$

where

$P_r$ = receiver sensitivity
$\lambda$ = wavelength
$P_t$ = peak transmitter power
c = speed of light
h = average height of rain volume
K = 0.95 as defined above

TABLE 2

QUICK FIX RADAR CANDIDATES

LOCATION/PENETRATION

| Designation | Function | $\lambda$ | $P_t$ | $\tau$ | G | $\theta^o/\varphi^o$ | $P_{min}$ (dBm) | |
|---|---|---|---|---|---|---|---|---|
| AN/APN 59 | Wx | 3.2 | 58 | 2 | 32 | 3/5 | -104 | AF |
| AN/APN 59 (MOD) | Wx | 3.2 | 100 | 2 | 36 | 2.5/2.5 | -107 | AF |
| AN/APS 42 | Wx | 3.2 | 50 | 2 | 32 | 4/4 | - 98 | AF |
| AVQ 10 | Wx | 5.6 | 75 | 2 | 28 | 5.2/5.2 | -100 | Commercial |
| AVQ 30C | Wx | 5.6 | 75 | 6 | 28 | 5.2/5.2 | -110 | Commercial |

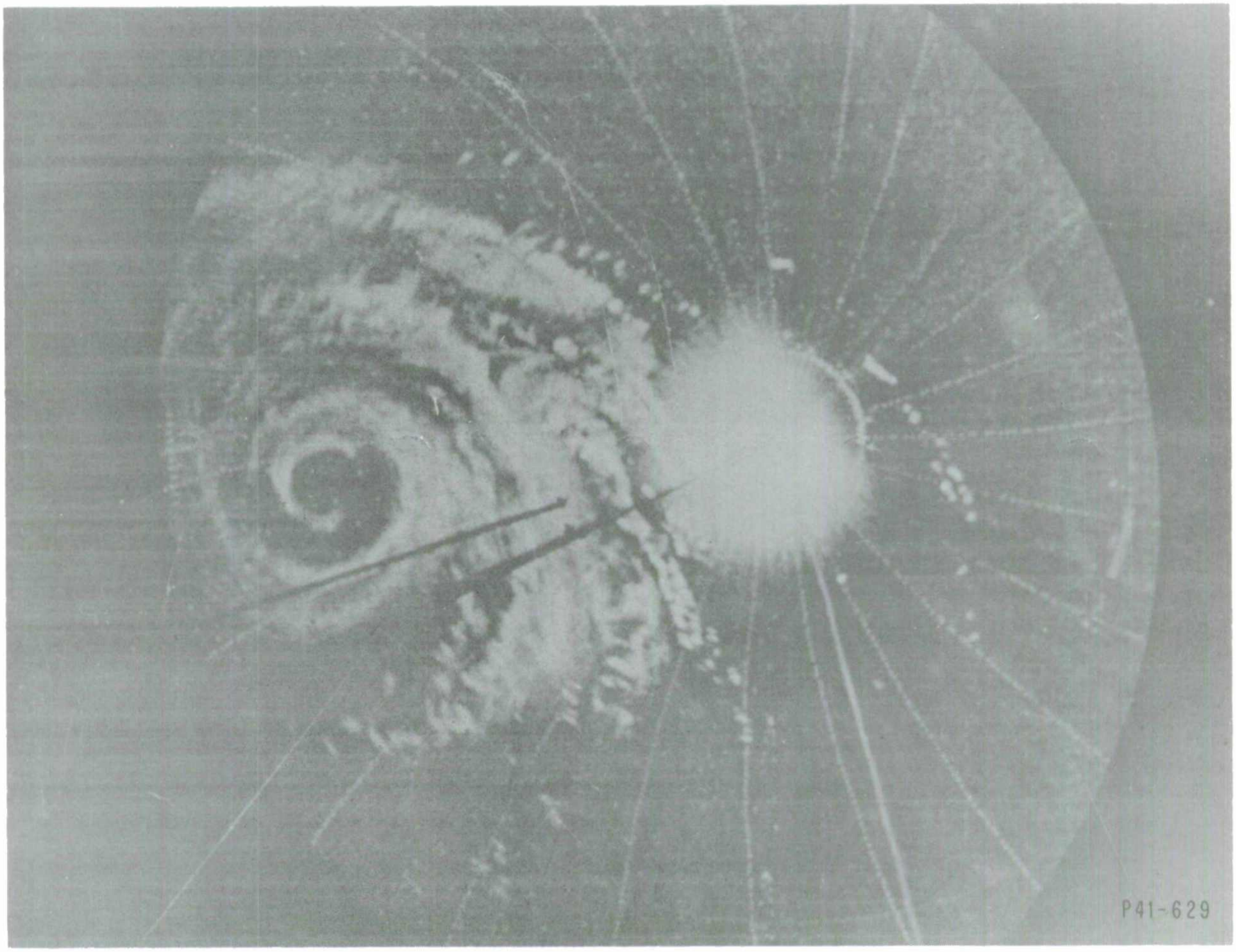



Fig. 13. Hurricane as seen from outside the storm by an APS-20 S-band radar on a Navy WV-2 aircraft. Off-center PPI display, 200-mile diameter.

TABLE 3

Comparison of Improved AN/APN-59 with AVQ-30C

| Parameter | APN-59 (improved) | AVQ-30C | Dimensions |
|---|---|---|---|
| Wavelength | 3.2 | 5.56 | cm |
| Pulse Length | 2.3 | 6.0 | microsec |
| Transmitter Peak Power | 100 | 75 | kilowatts |
| Receiver Sensitivity | $4 \times 10^{-14}$ | $1.36 \times 10^{-14}$ | watts |
| Beam Dimensions | $3^o/5^o$ | $5.2^o/5.2^o$ | horiz/vert |
| $Z_{100}$ (no attenuation) | 53.6 | 35.2 | $mm^6/m^3$ |
| $R_{100}$ (no attenuation) | .44 | .34 | mm/hr |
| $Z_{100}$ (6 mm/hr) | $2.5 \times 10^4$ | 163 | $mm^6/m^3$ |
| $R_{100}$ (6 mm/hr) | 21 | 0.88 | mm/hr |
| $Z_{100}$ (150 mm/hr, 12 km) | $5.4 \times 10^7$ | $1.1 \times 10^3$ | $mm^6/m^3$ |
| $R_{100}$ (150 mm/hr, 12 km) | $2.46 \times 10^3$ | 2.9 | mm/hr |

Two different rainfall models were used:

1. (6 mm/hr) indicates uniform rainfall at 6 mm/hr over the intervening 100 nautical miles.

2. (150 mm/hr, 12 km) indicates heavy rainfall, 150 mm/hr, concentrated in a band 12 kilometers wide, and assuming no rain in the remaining path of 100 nautical miles. This would be a reasonable model of an eye wall rain cell.

$R(s)$ = rain rate (mm/hr)

$\lambda_o$ = 4.54 cm, a constant

$\beta$ = $10^{-3}$ (km)$^{-1}$ (mm/hr)$^{-1}$, a constant

Table 3 shows that the antenna beamwidth has increased from 3.2$^o$ at X-band to 5.2$^o$ at C-band, but with no intervening rain attenuation, the detectability is essentially unchanged. For a uniform rainfall of 6 mm/hr, however, the sensitivity is far better at C-band (0.88 mm/hr at 100 miles) than at X-band (20.5 mm/hr at 100 miles), and for the heavy precipitation one might encounter in the eye wall, the X-band radar cannot see through it, while the C-band radar is still able to detect a modest rainfall of 2.92 mm/hr on the other side.

To enable the pilot to see what lies on the other side of intense rain, and to properly navigate to and in the center of the storm, we recommend that the APN-59 X-band radar be replaced with a C-band equivalent of the AVQ-30 C. This would require no modifications to the existing radome on the WC-130 which could easily contain the 30-inch diameter dish on which these calculations were based.

The advantage of this modification is that it can provide significantly improved performance immediately, i.e., in time for the 1970 hurricane season, if implementation is begun soon. Moreover, it is not likely that this radar need be changed to accommodate other near-term fixes in the future.

## XIII. OTHER NEAR-TERM IMPROVEMENT POSSIBILITIES

### A. Radiometry for Measurement of Sea Surface Temperature

We understand that equipment now used for this purpose on Navy reconnaissance aircraft is available commercially and should present no problems to early installation on the WC-130.

### B. Improved Navigational Aids

Experience has shown that not only are accurate fixes of the location of the storm center crucial to timely warning, but also other measurements dependent upon the navigation system provide important inputs to the forecaster. Flight level winds are now measured by determining the aircraft ground track with a Doppler radar navigator. At the shorter wavelengths, e.g., $K_u$ or X-band where these systems usually operate, difficulties in operation are encountered in heavy rain.

We suggest that an inertial reference system, updated by navigational satellite, Loran or Omega, or land fall sightings could provide a major improvement in navigational accuracies. Moreover, readouts from the inertial platform and its associated computer could provide flight level wind data, and something more than a subjective judgment of turbulence could be obtained from accelerometer outputs.

Although we have not made detailed comparative analyses, and we do not know of an airborne system in production, we expect the UHF/VHF reception of signals from the Navy navigational satellite to experience less difficulty in the severe storm environment than either Loran C/D or Omega which operate at much longer wavelengths.

C. On-Board Computer

Because of the rough flight conditions and the mass of data to be taken, we believe that the logging, preliminary reduction, and generation of displays of data should be automated to the degree practicable. Many of these tasks, now done manually or recorded in analog fashion on strip charts, could be handled digitally, enhancing the possibility of real time or near real time communication of these data to the ground.

D. Real Time Radar TV Repeater

We believe it would prove helpful in getting the most out of every hurricane mission to make it possible to transmit facsimile pictures of the radar display to the National Hurricane Center as requested or periodically. A preliminary analysis indicates that a PPI map (200 cells in range, 90 angular resolution cells, and 16 intensity levels) could be transmitted over a 2400 bit/sec satellite channel in half a minute. RHI pictures usually consisting of fewer bits could be transmitted in even less time. Lincoln Laboratory has demonstrated satellite communication of voice via multiple access satellites (e.g., LES-6). We are near an operational system for tactical communication with aircraft at UHF frequencies via satellites at synchronous altitudes.

## XIV. IMPLICATIONS OF RADAR REQUIREMENTS AS PRESENTED

From considerations such as range, loitering time, ability to penetrate severe storms, availability, and flexibility of interior configuration, the WC-130 is the practical choice of airframe for the short time period under consideration. Our consideration of the radar requirements is in this context. We also understand that the Navy has chosen the C-130 as the aircraft in which to implement its upgraded weather reconnaissance system.

A first priority requirement of the radar is that it display storm eyes 5 nautical miles in diameter at 200 nautical miles. Moreover, it must display the whole storm, the radar must penetrate regions of heavy rainfall and indicate rainbands on the other side, which rules out X-band or higher frequencies for this function. The higher frequencies will not provide adequate heavy rain penetration. This fact, coupled with the requirement that a 5-nautical-mile eye be resolved at 200 nautical miles implies a very narrow beam--hence, a large antenna.

To establish the beamwidth required to resolve the eye, assume that the nose of the beam is centered on the eye and consider the return at the center of the beam relative to that returned at the edge of the beam, say, where the sensitivity is down 20 dB. In order for the "hole" representing the eye to be 20 dB darker than its surroundings, viz., the eye wall, the horizontal dimension of the antenna must be 89 wavelengths. For a 10-dB difference in darkness between the eye and the wall, a 61-wavelength horizontal aperture would be necessary for resolution of the 5-nautical-mile eye at 200 nautical miles.

We consider the 20-dB level to be the best design choice. At the highest frequency that penetrates rain reasonably well, C-band, the antenna would have to be 16.4 feet wide (89 wavelengths at 5-cm wavelength). Operation at S-band would require a horizontal aperture of 32.8 feet.

Good vertical resolution is also desirable, but large vertical dimensions are hard to get on an aircraft.

With an aperture this large, the transmitter power and receiver sensitivity requirements are well within the state of the art.

Preliminary considerations indicate that a large scanning antenna ($\pm 70^{\circ}$), 16 ft by 7 ft, could be installed in an enlarged radome on the nose of the

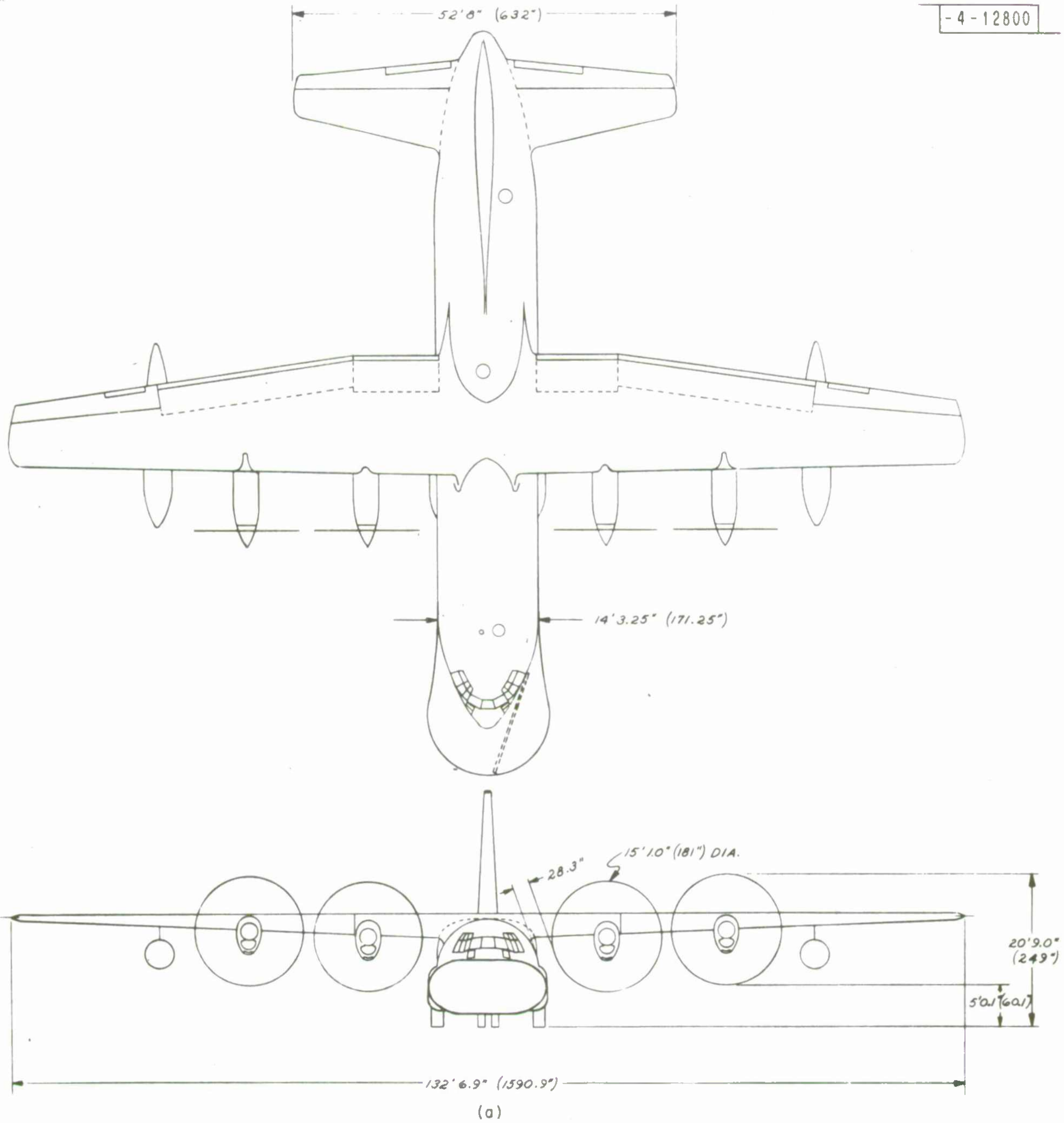
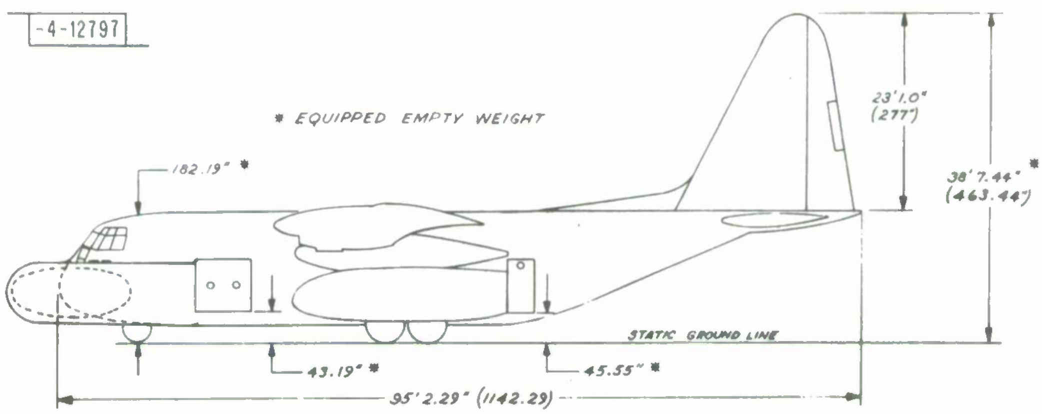



Fig. 14. Conceptual drawing of enlarged radome installed on the nose of the WC-130.




(b)

Fig. 14. Continued.

WC-130 (see Fig. 14). Dual-frequency operation, say, C- and S-band, would improve the flexibility of the system and allow potentially for the measurement of rainfall rate at S-band. The S-band horizontal beamwidth, less than $2^{\circ}$, is still reasonably good horizontal resolution.

The vertical beamwidths, $1.8^{\circ}$ at C-band and $3.6^{\circ}$ at S-band, are narrow enough to help differentiate between sea and rain returns.

Elevation tilt stabilization will be necessary to compensate for changes in aircraft roll attitude. Roll stabilization may not be necessary as long as the roll is small, say, less than 20 degrees. Elevation stabilization required will depend upon the roll angle.

Cloud height finding could be accomplished with the same antenna by incorporating a third frequency, X-band, or these measurements could be made with an APS-103 or equivalent system with antenna mounted on top of the aircraft.

We envisage no problem in providing range displays of 30, 100, and 200 nautical miles, nor with range accuracy of 2 nautical miles. If by azimuth accuracy we mean pointing angle, the $1^{\circ}$ accuracy should not be a problem.

The requirement of a five-level contour display of echoes implies a quantized system which in terms of echo levels in the receiver would not be difficult to display. If, however, the system is to assign a rainfall rate to each contour level, a compensated and calibrated system is implied. The $1/r^2$ range propagation loss can easily be accounted for, but if rain rate is to be quantitatively indicated, rain attenuation must be small enough to be ignored. Rain attenuation can only be ignored at the longer wavelengths, preferably longer than S-band, and only qualitative results will be obtainable using C-band wavelengths. There will be adequate penetration at C-band, but the interpretation of the significance of the contour levels would be all but impossible without independent determination of rain-attenuation in situ.

In summary, we see as the most critical requirement--the one of first priority--the use of a <u>large airborne aperture operating at C-band wavelengths or longer</u>.

XV. A NEAR-TERM CLOUD HEIGHT RADAR FOR THE WC-130

The AN/APS-45/X-band height-finder radar installed on the Navy WV-2 aircraft has a demonstrated ability to display the height of the rain bands in the hurricane wall cloud (Fig. 15). This information is important to the forecasters. In addition, the antenna can be rotated so as to give a PPI display (Fig. 16) showing the horizontal distribution of rainfall around the radar. If viewed from within the eye as in Fig. 16, the PPI displays the rainfall distribution in the eye wall clouds. If a radar of this kind could be installed on the WC-130 without diminishing its ability to penetrate severe storms, it would add significantly to the weather surveillance capability of this aircraft.

Candidates for the cloud height radar appear in Table 4. The AN/APS-103 is the height-finder radar installed in the EC-121 AEW aircraft. It is like the APS-45 in all respects except it has twice the peak power. At the outset, the C-band APS-44 appeared to be a good candidate system which has the advantage of lower attenuation, but we have learned that very few of these sets were ever produced, and their whereabouts are unknown.

Since all three operate at X-band, it is interesting to compare the sensitivities of the three radars--APN-59, APS-45, and APS-103. In doing so, we find that the APS-45 has nearly 40 times more sensitivity than the standard APN-59, and the APS-103 has twice the sensitivity of the APS-45.

We discussed with Lockheed personnel the possibility of mounting an AN/APS-103 radome on the WC-130. It was their opinion that the radome could not be mounted on the WC-130 as it was on the EC-121 without affecting the lateral stability of the aircraft. They suggested that the only way in which the APS-103 antenna could be accommodated on the WC-130 was to design a new radome as part of the empennage. This would require a minimum of a year because it involves both microwave and aerodynamic proof testing.

The magnitude of the modification implied by the installation of the APS-103 on a few WC-130's as an interim improvement in instrumentation

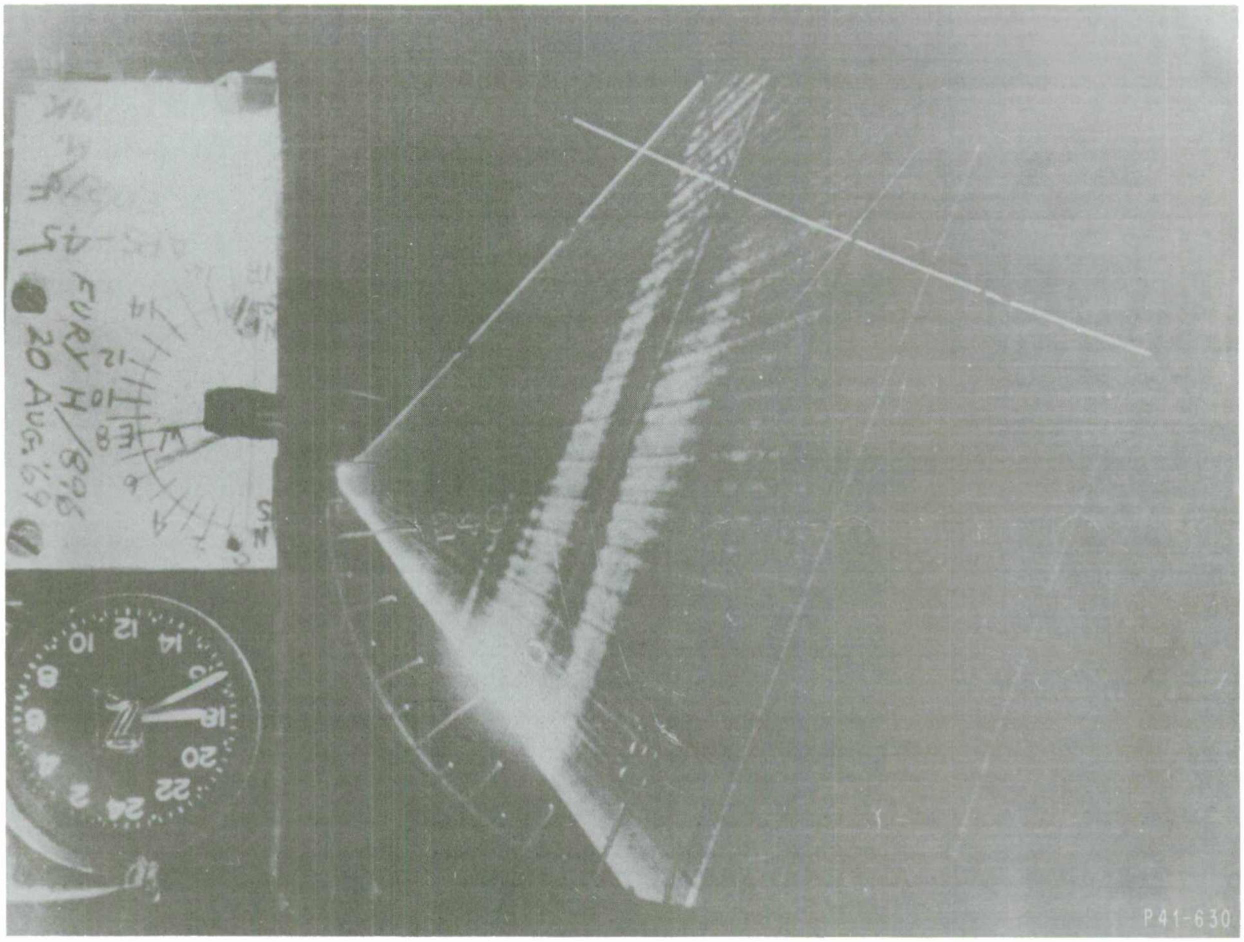



Fig. 15. Photograph of the range-height indicator scope of the APS-45 radar on a Navy WV-2 aircraft.

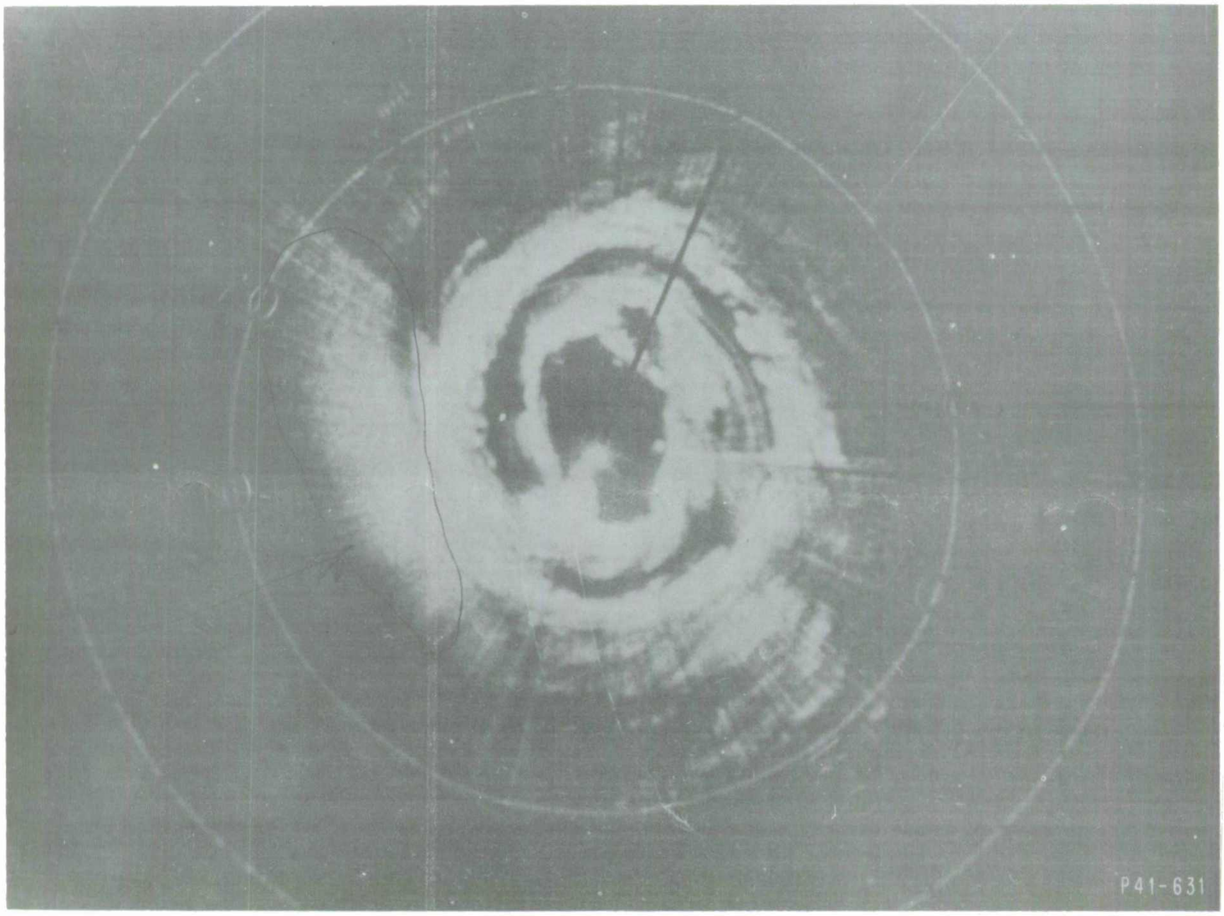



Fig. 16. Photograph of the PPI display of the APS-45 radar on a Navy WV-2 aircraft. Photo taken from inside the eye of the storm.

TABLE 4

INSTRUMENTATION RADAR CANDIDATES

| Designation | Function | $\lambda$ | $P_t$ (kW) | $\tau$ ($\mu$ sec) | G (dB) | $\theta^o/\varphi^o$ | $P_{min}$ (dBm) | |
|---|---|---|---|---|---|---|---|---|
| AN/APS-45 | RHI/PPI | 3.2 | 480 | 2 | | 3.1/1.2 | -107 | Navy |
| AN/APS-103 | RHI/PPI | 3.2 | 1000 | 2 | | 3.1/1.2 | -107 | AF |
| AN/APS-44 | PPI/BOMB | 5.6 | 1000 | 2.35 | 40 | 1/2.6 | -106 | Navy |
| | | 3.2 | 480 | 2.35 | 36 | 3.2/3.2 | -100 | |

radars for circa 1971 has some mitigating factors:

(1) Because the APS-103 functions as a height finder, the installation of a second radar to provide this function would be unnecessary.

(2) The narrow vertical beam would provide high resolution data on the vertical structure of the rain clouds observed.

(3) Its improved sensitivity to light rainfall would enhance its usefulness in weakly formed storms under investigation in its PPI mode.

(4) The equipment is in the inventory and there is Air Force experience in its operation and maintenance.

(5) We understand that there are over twenty EC-121/H's equipped with APS-95 and APS-103 radars at the Davis Monthan "bone yard."

(6) Both the EC-121 and the C-130 were built by Lockheed. Experience with the mounting of the radome on the Constellations should prove valuable and shorten the design and modification time of the C-130's.

(7) The proximity of the contractor to the Warner-Robbins Air Material Area might also aid speedy modification.

## XVI. CONSIDERATION OF AN UPDATED VERSION OF THE AN/APS-20E

From the point of view of installing in the WC-130's a radar with which we have had extensive experience both as weather radar and as an AEW radar, there is much to be said for installing a modernized version of the APS-20E. The principal problem anticipated in this approach is the mounting of the large radome and antenna (14 to 18 ft horizontal, 3.5 to 4.5 ft vertical). This is large enough to have a significant effect upon the flight characteristics of the aircraft, and may even jeopardize the aircraft's ability to penetrate the more violent storms.

The included angle of a 5-nautical-mile diameter eye at a range of 200 nautical miles is a fortieth of a radian. As discussed before, what is required in terms of antenna dimensions to resolve the eye will depend upon the definition that one accepts for resolution. If one accepts one of the optical definitions, the angular distance from the nose of the beam to the first null (approximately the half-power beamwidth), our antenna would have to be 40 wavelengths wide, or about 14 ft at a wavelength of 10.4 cm. (Assuming a 55% illumination efficiency, a 14-ft aperture would give $1.6^{\circ}$ half-power beamwidth--nominally that of the APS-20E.) We do not believe that this resolution is adequate to resolve the 5-mile-diameter eye at 200 nautical miles on an ordinary radar PPI. To do this, the aperture would of course have to be larger.

The relatively large vertical beamwidth of the APS-20 radar antenna as it now exists ($6^{\circ}$) may prove troublesome at long ranges (200 nautical miles) where the vertical beam would encompass about 20 miles. The vertical extent of hurricanes rarely exceeds 50,000 ft, and the region of most interest from the point of view of accurately locating the eye is that between 1,000 and 50,000 ft altitude.

Because of the low ground clearance of the WC-130, it would not be practical to mount a radome under the fuselage as was done on the EC-121's. It would not be out of the question to mount a radome on the nose of the aircraft to accommodate an antenna of this size, nor would it be unreasonable to consider an EC-121-like radome mounted on top of the fuselage.

The major parameters of the APS-20E need not be changed much from what obtains now. One could expect, however, to get some improvement in receiver sensitivity and dynamic range, and to include a form of sensitivity time control more adequately matched to the weather surveillance problem than to AEW. Iso-echo contours could be included without difficulty if quantitative rainfall attenuation compensation were not required.

The principal advantage of this approach is that we would be providing a system with which we have had experience--we know it works reasonably well--and that there can be little question that the system is state-of-the-art. The principal obstacle would be the installation of an antenna of that size on the WC-130 without compromising its ability to penetrate hurricanes.

## XVII. LARGE AIRBORNE ANTENNAS

### A. Past and Present Experience

Most of our past experience in flying large antennas has been in connection with airborne early warning systems which have, typically, antennas located in radomes which are about 25 ft by 3 ft in size. One early version was the Navy's WF-2 or E-1B Tracer carrier-based AEW aircraft built by Grumman. The radome on this small aircraft measured 20 ft by 30 ft horizontally and about 2-1/2 ft vertically. Normal take-off weight was under 30, 000 pounds. The carrier-based aircraft of the 1960's were the E-2 series, also by Grumman and called the Hawkeye. Nominally, the same size antenna was carried in this larger more powerful aircraft which had a take-off weight of about 50, 000 pounds. The version of the Hawkeye now in production is the E-2C equipped with the UHF APS-111 radar (Fig. 17). The antenna size on the E-2 would give a $1^{\circ}$ horizontal beamwidth at S-band and about a half-degree beamwidth at C-band. Vertical beamwidths would be about an order of magnitude greater.

We checked the feasibility of flying this kind of aircraft in hurricanes. While the airframe has taken 6g forces, and test pilots who have flown it suggest it is as sturdy as the C-130, it is a calculated risk to take it into a hurricane. If, for example, hail were encountered, the fibreglass radome and vertical tail surfaces could suffer severe damage. Designed to be based on an attack carrier, the range of the aircraft is limited to something like 5 hours on station at 200 miles at altitudes of 20, 000 to 30, 000 ft. There has been designed a "wet wing" version of this aircraft which can loiter 7.6 hours on station at 200 miles.

In the WV-2E version of the Lockheed Constellation, a large disc-shaped radome was carried on a pylon above its fuselage. We were unable to get additional information on the operation characteristics of this aircraft.

Large surveillance antennas have also been carried inside the gas bag of a Navy blimp. However, a blimp is the last thing one would want to fly in the neighborhood of a severe storm system.

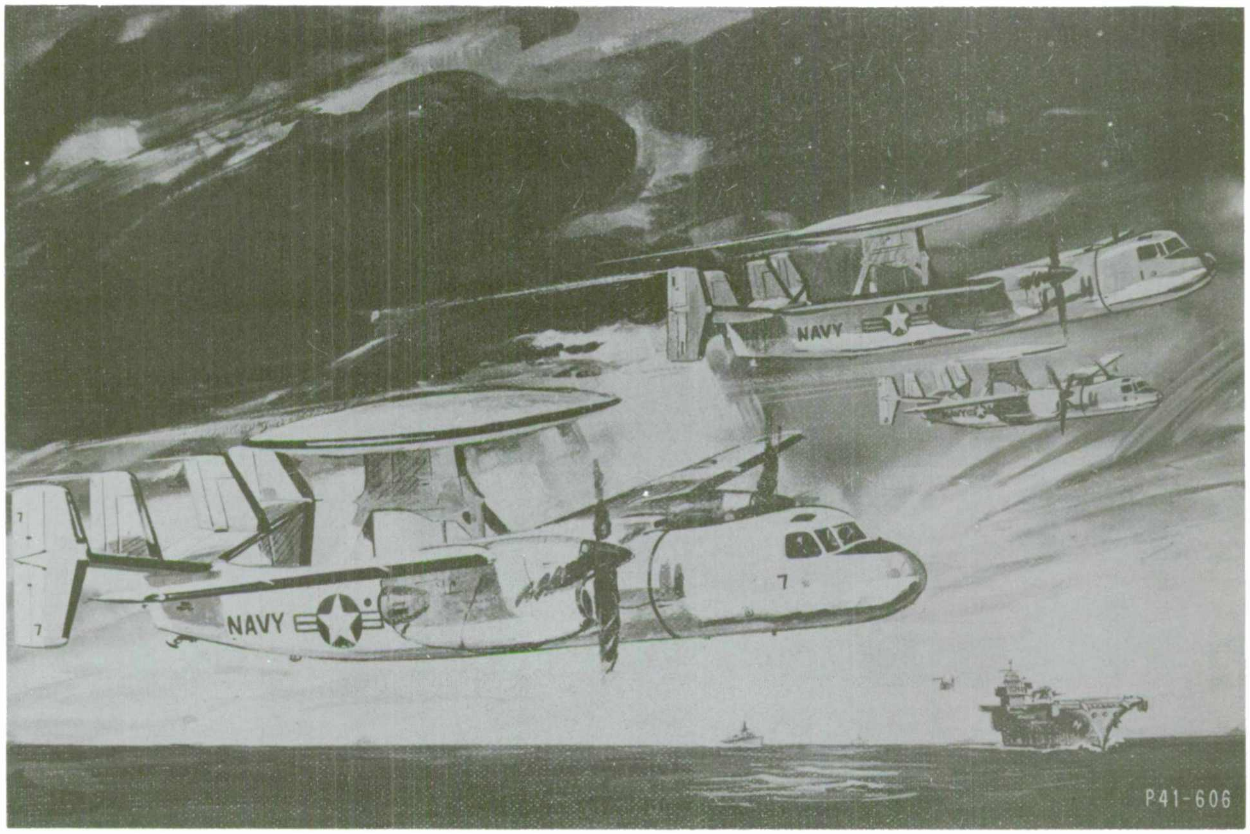



Fig. 17. Large radome mounted on the Navy's E2-C aircraft. (Grumman photograph.)

B. Future

The Airborne Warning and Control System radar development envisages use of a 30-ft by 7-ft radome. Large disc-shaped radomes mounted on top of the vertical empennage are being considered for both the Boeing 707 version and the McDonnell-Douglas DC-8 version of this aircraft.

Frequently suggested and infrequently implemented are conformal phased arrays as a method of getting large apertures on aircraft. These, as well as various configurations of deployable and fixed phased arrays, might well be considered, but associated problems are likely to be difficult. We expect, of course, that array design will be strongly affected by the airframe design, since this country seems to be unable to make the compromises needed to design a special airframe for the express purpose of carrying airborne instrumentation aloft.

## XVIII. DOPPLER RADARS FOR WEATHER OBSERVATION

The only Doppler radars now employed in routine weather service observation are Doppler navigation systems which are used with true air speed indicators to obtain wind velocities at flight level. Doppler radar has been used but only on an experimental and ad hoc basis by several research groups.*

Because the radar targets are raindrops primarily, a measurement of their velocity would indicate raindrop radial velocity relative to the aircraft. A relation would have to be derived between rain velocity and maximum wind velocity.

To avoid excessive Doppler spread, the Doppler radar needs good range and angle resolution. Because the target is a volume distribution of randomly disposed scatterers, we will be unable to use some of the pulse compression, burst, or other techniques which work so well for point targets, nor will we be able to use just any prf or frequency-jumping scheme to resolve Doppler ambiguities. Our pulse-Doppler radar may well have to be unambiguous both in range and in Doppler in the region of interest.

---

*E.g., Armstrong and Donaldson, Ref. 10.

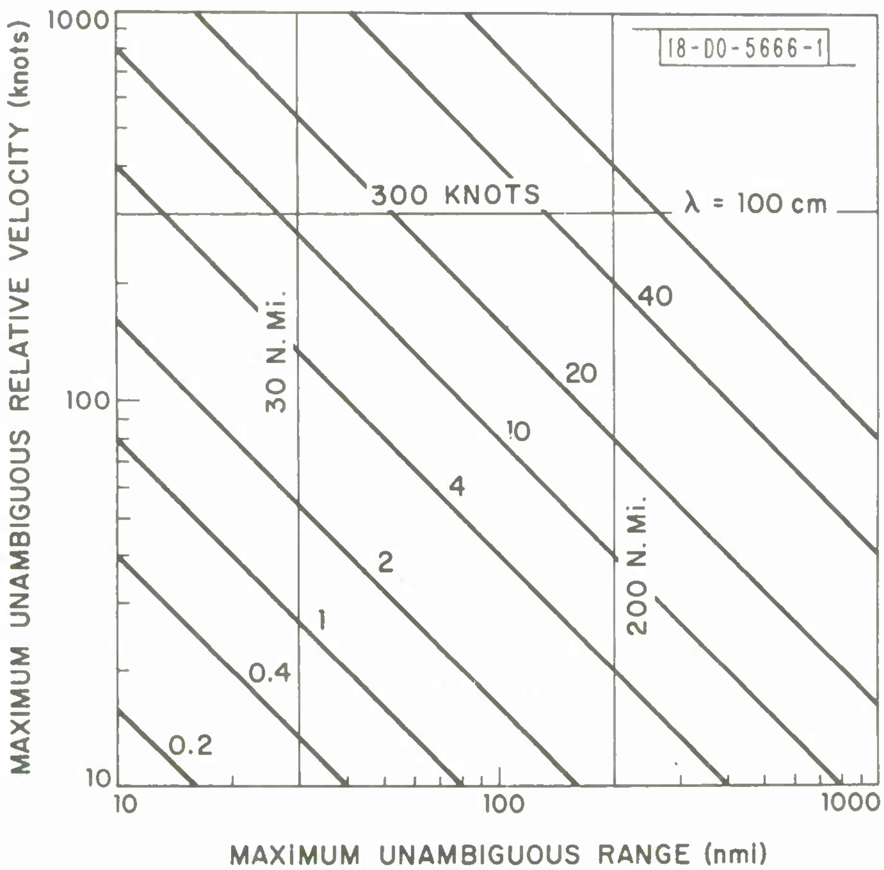



Fig. 18. Maximum unambiguous relative velocity vs maximum unambiguous range for a pulse Doppler radar with operating wavelength as a parameter.

Figure 18 shows, for example, that to have the first blind speed at 300 knots and the first range ambiguity at 200 nautical miles, one would have to operate the radar at a wavelength of about 50 cm. To retain the first blind speed at 300 knots and to operate at 10-cm wavelength would limit the maximum unambiguous range to about 30 miles. Reducing the range at which observations are made has the further advantage of making the resolution volume smaller for the same antenna beamwidth.

The short unambiguous range interval leads to the probability of second time around echoes from heavy rain bands in the succeeding range interval. It is not yet clear how these could be discriminated against with ordinary Doppler techniques.

Single-frequency, staggered prf techniques appear to have promise, especially if used in a system of multiple observations of the same spatial location from different aspect angles. The multiple-look capability would also aid in determining the true horizontal velocity, not just the radial velocity of the rain relative to the aircraft.

In spite of the difficulties described above, we feel that coherent Doppler systems should be explored further for application to weather observations.

## XIX. A LONG-TERM RESEARCH, DEVELOPMENT, AND PROTOTYPE TEST PROGRAM

### A. General

Most tropical storms develop from wave disturbances originating in regions remote from land-based sensors. Satellite reconnaissance of cloud formations has provided meteorologists with a means of locating hurricane "seedlings" which may develop into threatening storm systems.

About one seedling in ten develops into a major tropical storm which then gets a name. It was not possible until 1967 to follow the course of a tropical disturbance from near the African coast where it developed across the Atlantic and through the Caribbean. Such storms, spanning about 1000 nautical miles, take the order of days to traverse the Atlantic. With reconnaissance satellites, many storms are now detected in their incipient stage, but their position must be monitored and their characteristics probed from short distances by reconnaissance aircraft to determine the nature of their threat to ships at sea and land areas.

In a paper given at the 1969 National Hurricane Conference, Neil Frank indicated that the African wave disturbance was the source of the greatest number of seedlings which later developed into major storms. Once a threatening tropical cyclone has been detected, the problem of dynamical prediction of the hurricane track commands the attention of forecasters. For example, data obtained from reconnaissance aircraft and conventional surface maps have been used by Frederick Sanders to predict successfully, by a procedure of direct analysis, the track of one hurricane. The data needed for this kind of forecasting include the windfield averaged over the 1000-mb to 100-mb layer, the calculation of a stream function for this windfield, and baratropic predictions for 72 hours. Preliminary tests indicate reasonable success in forecasting the tracks of a wide variety of tropical storms. The ex post facto predictions of the track of hurricane Camille using this technique were remarkably successful.

While the impetus for the present upgrading of the reconnaissance aircraft stems from incidents associated with hurricane Camille, it is important to remember that the evolution of more advanced forecasting techniques such as those mentioned above and the likely future use of weather modification procedures will place additional demands on the airborne weather reconnaissance system. There is no instrumentation grade, airborne weather radar in the inventory at this time which will obtain quantitative data on rainfall intensity, cloud height, and other storm parameters. Yet such data are essential to meteorologists concerned with the development of storm models and advanced forecasting techniques. The aforementioned salient parameters, plus sea temperature, are needed in future operations to supplement the in situ measurements currently made by the reconnaissance aircraft.

Any major upgrading of the aircraft instrumentation which is expected to carry them the 10 to 14 year life of the airframe should attempt to provide a truly augmented sensory capability. Moreover, suitable data formatting and recording facilities are needed to make data obtained on airborne reconnaissance missions most useful to those studying the meteorological dynamics of the storm.

For the long term, therefore, we believe that it is essential that the instrumented severe storm reconnaissance aircraft be designed from the over-all systems point of view. The radar, for example, cannot be considered as an isolated problem because so much of what it has to do depends upon operational constraints, airframe constraints, observations needed, data reduction required, possibility of multi-unit observations, navigation, communications, and other instrumentation.

Because of the hazards of penetration of severe storms, we would work to obviate the necessity of penetration by making it possible to locate and assess the severity of the storm from outside the eye. To do this with radar alone would require a system capable of displaying the whole storm and a well-defined eye, plus the ability through Doppler measurements to ascertain the maximum winds. Beacon-assisted radar and the use of other means of penetration, i.e., high-performance aircraft penetrators, drones, chaff, super-pressure balloons, etc., would be a quite different system.

The importance of an automatic integrated, reliable navigation system cannot be overemphasized, nor can the provision of an on-board data reduction facility with a concomitant high-grade communications system that has the ability to get the important data to the place it is most needed without delay.

B. Communications

We believe it is essential to provide real time communications between the reconnaissance aircraft and its data users. Important alterations of flight plans could be accomplished in view of unforeseen developments in data or as a result of information from other sources.

We would propose that data such as radar altitude, pressure, humidity, aircraft position, wind velocity, dropsonde measurements, etc., be continuously transmitted to the National Hurricane Center. Each of these data can require only about one bit per second. A satellite communication link established using a 2400 bit/sec vocoder would provide a diversity of possibilities, data, PPI maps, and RHI maps, in addition to reliable voice communications. Low-data-rate information could easily be incorporated in the 2400 bit/sec channel by interpolating it into the silences or even into the unvoiced portions of the speech. The possibilities of transmission of RHI and PPI pictures over satellite communications channels have been discussed earlier.

## XX. OUTLINE OF SUGGESTED WEATHER RADAR PROGRAM (2-year period)

I. Systems Analysis (first through eighth month)
   - A. Required Meteorological Measurements
   - B. Airborne Instrumentation - Data Processing, Recording, Relay
   - C. Navigation - Interface
   - D. Communications - Telemetry

II. Develop Prototype Radar (sixth through eighteenth month)
   - A. Exploit Use of Doppler Measurement, Multiple Frequency Altitude Measurement Capability, etc., for Next-Generation System
   - B. Work with Airframe Manufacturer to Evolve an Integrated Plan

III. System Integration (fourth through twenty-fourth month)
   - A. Develop over-all plan for integrated radar, communications, navigation, on-board computer, displays, real time command and control capability, etc.

IV. Flight Test (sixteenth through twenty-fourth month)
   - A. Install Experimental Systems in Aircraft and Conduct Flight Evaluation Test
     1. In Hanscom area
     2. In Puerto Rico

## BIBLIOGRAPHY FOR FURTHER REFERENCE


1. Petterssen, Sverre, Introduction to Meteorology, 2nd Ed. (McGraw-Hill, New York, 1958).

2. Hewson, E. Wendell, and Longley, Richmond W., Meteorology Theoretical and Applied (Wiley, New York, 1944).

3. Tannehill, Ivan Ray, Hurricanes (Princeton University Press, Princeton, 1952).

4. Dunn, Gordon E., and Miller, Banner I., Atlantic Hurricanes (Louisiana State University Press, 1960).

5. Riehl, Herbert, Tropical Meteorology (University of Chicago Press, 1959).

6. Battan, Louis J., Radar Meteorology (University of Chicago Press, (1959).

7. Norton, Chester W., "Severe Convective Storms," Advances in Geophysics, Vol. 12 (Academic Press, New York, 1967), pp. 257-308.

8. American Society for Oceanography, Publication No. 1 "Hurricane Symposium," 10-11 October 1966, Houston, Texas.

9. Atlas, David, "Advances in Radar Meteorology," Advances in Geophysics, Vol. 10 (Academic Press, New York, 1964), pp. 318-468.

10. Armstrong, Graham M. and Donaldson, Ralph J., Jr., "Plan Shear Indicator for Real-Time Doppler Radar Identification of Hazardous Storm Winds," J. Appl. Meteorol. 8, 376 (1969).

APPENDIX I

MEMORANDUM OF RECORD 2 December 1969

From: J. W. Meyer

Subject: Interim Memorandum Report on Seek Storm Radar Study

Introduction

Following a meeting on 4 November 1969 between a group of Lincoln staff headed by H. G. Weiss and ESD personnel representing Colonel Galt (Mr. E. Thomas and Mr. S. Malgari), a study group was formed consisting of the following people: R. Crane, M. Labitt, J. W. Meyer, C. E. Muehe, C. M. Rader, and M. L. Stone. The group was to explore possible modifications to the existing radar and weather instrumentation for the near term and to formulate the design of an advanced weather radar instrumentation system properly interfaced with other instrumentation and compatible with the constraints imposed by the WC-130 aircraft. The study was to be guided by some very general specifications outlined by ESD and discussed in our 4 November meeting.

On 10 November a group of us discussed the problem of radar surveillance of hurricanes with members of the M.I.T. Meteorology Department, including Profs. Houghton, Newell, Sanders, Dr. P. M. Austin and S. G. Geotis. Prof. Sanders had just returned to M.I.T. after a year at the National Hurricane Center and provided valuable first-hand information about the hurricane surveillance problem.

During our discussion we attempted to establish an order of importance of the hurricane surveillance functions the radar system might perform. They are:

(1) Locate the storm and track it.
(2) Measure maximum horizontal wind at the top of the inflow layer. (Because precipitation occurs most of the time in this layer-- 1 - 1.5 km altitude--radar Doppler measurement of this wind may be possible.)
(3) Provide the pilot with information needed to enable the aircraft to safely penetrate the storm. (When not measured directly as above, the maximum winds are deduced from an empirical formula devised

by Fletcher,

$$v_{max} = 16\sqrt{p_n - p_o},$$

where $v_{max}$ is the maximum wind in knots, $p_n$ and $p_o$ are the pressures in millibars along the periphery and at the center of the storm, respectively. As they are currently made, these measurements require penetration of the storm.)

Penetration of the most severe storms can be extremely hazardous. The Navy lost a hurricane hunter and all hands in Hurricane Janet in 1955. Several hurricane reconnaissance planes have also been lost in Pacific typhoons. Flight safety regulations now forbid Navy penetration of the stronger storms. We feel that the radar can provide an important margin of safety when the most severe storms are encountered by providing a Doppler measurement of wind maxima from outside the storm. In those cases where it is relatively safe to penetrate, radar data can be compared with measurements made by the pressure difference method.

(4) Measurement of sea state through interpretation of radar sea return. (It has been possible to locate the eye of hurricanes by observing the hole in the sea return. Sea return prints of hurricanes have been observed on UHF AEW radars which, because of their long wavelength, see little precipitation echo.)

If sea clutter analysis can be made in a fashion that will permit deduction of maximum winds from sea state measurements, this will provide valuable additional data. Moreover, because the sea state will lag, to a degree, the wind eye of the storm, simultaneous measurements of the sea clutter eye and the precipitation eye might provide a vector indication of the storm's motion. Since it is known that swells radiate out from the storm center for hundreds of miles, the strongest of which usually originate from the right front quadrant, mapping and analysis of these wave phenomena might aid in locating the storm.

Two of the study group are attending a hurricane conference in Miami this week and will take advantage of this opportunity to discuss severe storm detection and measurement problems with the assembled experts.

## Approach to the Radar Problem

For the radar we identify three time frames: immediate, near term and long term. For the immediate case our recommendations must be in the context of the existing program; limited modifications would be possible in the near term; and the long term should define the best system consistent with the physical constraints and boundary condition.

The WC-130 is a commodious aircraft but does not have unlimited space and prime power resources. Also, the installation of radar antennas and radomes must not affect the performance of the aircraft too severely.

## A Radar Model of a Hurricane

There is no canonical hurricane, tornado, or any other violent storm for that matter. There is considerable variance in individual cases from any "average" storm one might devise. Yet we do need a model against which we can check our proposed design configurations. The definition of this model is one of the study's main objectives. Fortunately, we do have considerable radar experience with violent storms. We know the parameters of the APS-20 radar, for example, and have numerous recorded instances of hurricane detection and tracking. We have similar experience in other wavelength regions and the radar meteorological community has worked extensively at comparing rainfall rates as measured with rain gages with the rates measured by radar.

## Factors Affecting Radar Configuration

It is important to provide a map of the rainbands of the storm. A map can be formed with a rotating antenna and a PPI display, a sector scanning antenna with appropriate display, or a fixed narrow beam side-looking antenna which can form a rectilinear map display with the aircraft motion. Phased array configurations are possible in these cases too.

The intensity of the rain and its distribution in space affect the choice of volume resolution, the dynamic range required of the receiving system, and the degree to which total attenuation must be compensated. Given enough power and antenna aperture, weather phenomena can be observed with longer wavelengths. High resolution rain cell measurements are easily made at minimal rainfall rates with the L-band Millstone radar, for example. By way of contrast, storms associated with the Worcester tornado of 1953 were dramatically displayed on a relatively low powered TPS-1D L-band MTI radar operated at Lincoln Laboratory.

To avoid difficulties in the interpretation of data, the operating wavelength should be large compared with the drop size of the precipitation (Rayleigh scattering).

For the measurement of wind velocity, pulse Doppler techniques, and active and passive probes have been suggested. The possibilities of chaff, superpressure balloons, drones, modified air-to-air missiles will be considered as potential aids to remote wind measurement with radar. A beacon or a burst chaff dispenser on a modified Sparrow might provide a reasonable means of safely penetrating a most severe storm at a variety of altitudes.

## Choice of Wavelength

The choice of wavelength is always a studied compromise between many conflicting factors. Good spatial resolution tends to shorten wavelengths. Ambiguity problems in Doppler radar design dictate longer wavelengths, particularly for longer range radars. The nature of the target, whether a suspicious tropical depression or a mature storm, provides a wide range of precipitation levels. To a degree, the decreased sensitivity of the longer wavelengths to lower precipitation rates can be made up for with increased system performance, but there is a limit to how far one can go in fighting the $1/\lambda^4$ scattering law for small particles, particularly in an airborne system.

## Advantages and Disadvantages in the Various Wavelength Bands

L-band: This band allows easier Doppler design and targets are well in the Rayleigh scattering region. A larger real aperture is needed for resolution. The magnitude of precipitation scattering cross section is small.

S-band: Moderate Doppler design problems. Dual or multiple prf modes may be required. Target particles getting larger with respect to wavelength which may produce some anomalies. Smaller aperture needed for resolution and the magnitude of the scattering cross section is greater.

X-band: Doppler design difficult. Heavy precipitation particles getting commensurate with the wavelength. Scattering and total attenuation large. One not likely to see through a severe storm. Some clouds visible.

$K_u$-band: Has all the X-band problems. Could have best cloud indication for surveillance of immature storms.

Other Factors

The height of Atlantic tropical storms rarely exceeds 50,000 feet. At or above this level there is little severe turbulence, so the question arises as to what measurements on the storm can be made from on top. A mapping radar looking down from the aircraft would need only a limited range, the maximum range at about eight miles being emphatically marked by the sea surface return. The need of only a small range allows use of a very high prf which in turn helps avoid the problem of Doppler velocity ambiguities. A relatively fine grain analysis of vertical motion in the rain bands could be made with a range-gated Doppler radar which, because of the limited total range required, could be operated effectively at X-band in spite of the large total attenuation likely in this band.

Overflight would also permit dropsonde measurements. Chaff, corner reflector, or beacon drops could be made for further radar analysis of storm circulation.

The importance of a good navigation system adequately interfaced with the radar tracking system cannot be overemphasized. It appears, however, that current operational systems such as the Omega or Loran C/D would serve this purpose quite adequately.

## Conclusion

We have found the Report to the Administrator ESSA on Hurricane Camille (12 September 1969) to contain much information useful to this study. In addition, the National Hurricane Operations Plan (April 1969) contains a wealth of information important to our system studies.

As we continue these studies the ideas presented above as well as others developing later will be accepted and developed, or rejected on the basis of probable performance within the physical constraints against our radar model storm.

Besides developing a model, we are conducting a parametric study of radar systems to get a better understanding of what can be exchanged for what in the adjustment of the many parameters. Data processing techniques are also being studied, but fine definition of this problem area must await further consensus on proposed radar parameters.

We plan to maintain close contact with the Sugg study of instrumentation requirements being carried out under the auspices of ESSA. We expect to improve our understanding of current procedures for forecasting and analysis, and to get more detailed information on the measurements required and desired, as a result of contacts made at the Hurricane Meeting in Miami, in addition to our continuing interaction with members of the M.I.T. Department of Meteorology.

Current radar performance for a few systems is tabulated in the appendix which establishes a kind of "bench mark" with which new system approaches can also be compared.

We have prepared a draft outline of our report and have made assignment of responsibility for the several sections identified.

## APPENDIX II -- BRIEFING AGENDA

M.I.T. LINCOLN LABORATORY

WEATHER RADAR STUDY FOR
ESD AEROSPACE INSTRUMENTATION PROGRAM OFFICE
WEATHER RADAR STUDY BRIEFING

18 December 1969

| | | |
|---|---|---|
| I. | Introduction | H. G. Weiss |
| II. | Hurricane Camille/Meteorology | R. K. Crane |
| III. | Problem as Seen by ESD | J. W. Meyer |
| IV. | Trip Reports/Our Response | M. L. Stone |
| V. | Radar Possibilities/Recommendations | M. Labitt |
| VI. | Other Quick-Fix Possibilities | M. L. Stone |
| VII. | Communications | C. M. Rader |
| VIII. | Long-Term LL Program | H. G. Weiss |

## APPENDIX III

## DOPPLER FILTERING FOR AN AIRBORNE WEATHER RADAR

Doppler filtering of precipitation returns from a large storm is a problem not usually encountered in MTI radars observing point targets. A large storm may be 200 nautical miles in extent so that a high pulse repetition rate to eliminate Doppler unambiguities cannot be used because of hopeless confusion in determining the shape of the storm and interpreting at which spot in the storm the precipitation velocities are being evaluated resulting from numerous range ambiguities.

If a uniform pulse train of 400 pps is used at S-band, the first velocity ambiguity occurs at 46 mph. Now, hurricane winds may approach 200 mph, and it is desirable to measure the wind velocity to 10 percent accuracy or better. Remembering that the wind can have either positive or negative Doppler, there would be about an eightfold Doppler ambiguity using a single uniform pulse train.

Two solutions to the Doppler filtering problem appear possible. The choice between them depends on the Doppler spectral spread likely to be encountered.

The first uses two pulse trains, one at 400 pps, the other at 365 pps (8/9 x 400). Pulse trains, say 64 pulses long, and analog or digital filters could be used. The Doppler spectral response from a storm with quite uniform wind velocity is shown in Fig. III-1. The two spectra would be cross correlated to find the most likely shift in position in the filter banks. From this shift the velocity could be determined. Unfortunately, in many cases the spectral spread may be much greater than that depicted in Fig. III-1, and the two samples, being statistical in nature, will not produce a narrow spike upon cross correlation. These subjective observations should be examined more closely. We need better information on wind velocity distributions likely to be encountered in severe storms. Because of these difficulties, an alternate scheme might be better.

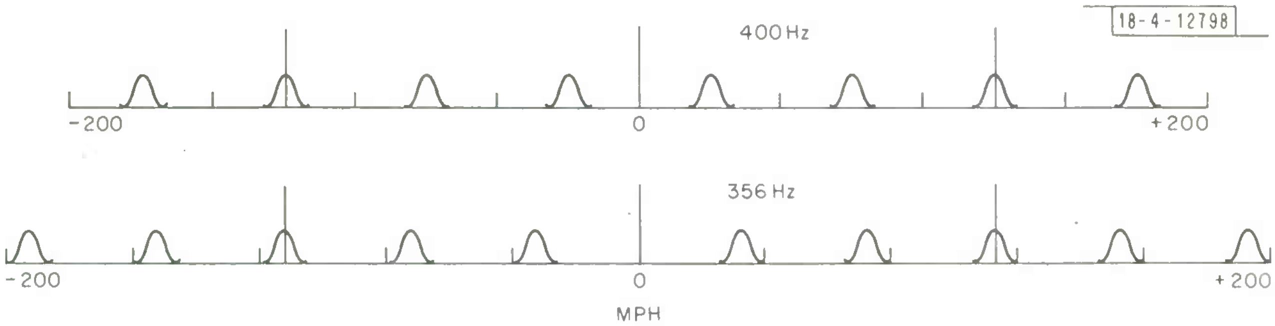



Fig. III-1. Velocity ambiguity diagram for two repetition notes.

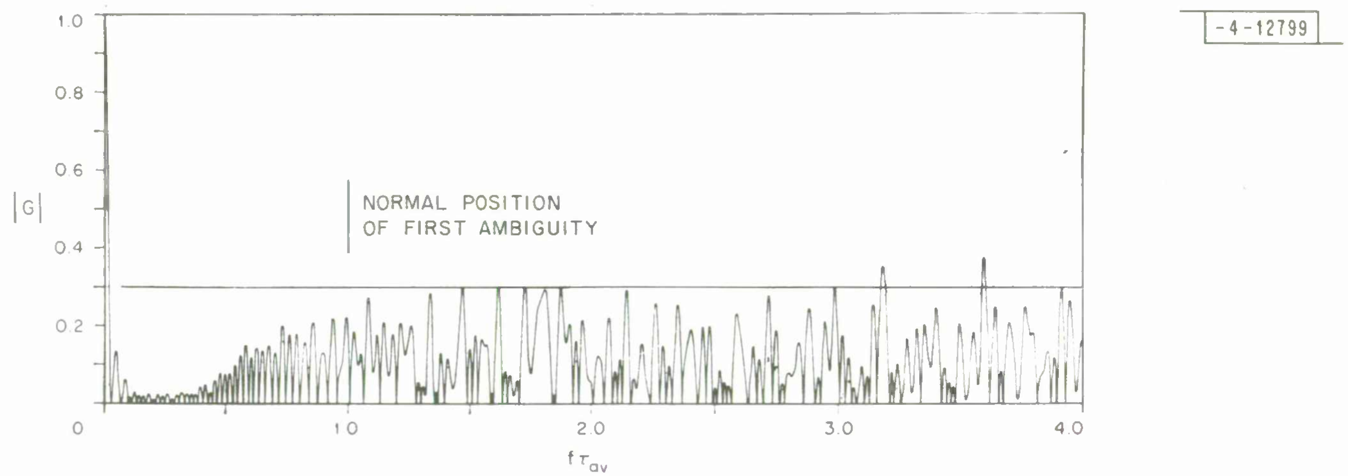
In the second scheme a staggered repetition rate is used in a fashion completely analogous to that of varying the inter-element spacing in a linear array antenna to permit wide element spacing and yet avoid grating lobes. Andreasen* has developed spacing arrangements which give reasonably low sidelobes out to four times the normal position of the first grating lobe (see Fig. III-2). By substituting $f \tau_{av}$ for the ordinate label in Fig. III-2, the graph applies to the Doppler filter response to be expected when using pulses spaced an average of $\tau_{av}$ apart and spaced according to the table supplied in Fig. III-2.

The peak sidelobe level is only 10 dB down, but the average is probably closer to -17 dB. The width of the main lobe is approximately $1/N \tau_{av}$, where N is the number of pulses, so that 8N filters would be built. Since this fine spectrum resolution is not needed, spectral smoothing could be accomplished by non-coherently adding several (about 10) appropriately weighted, contiguous, filter outputs.

The Doppler signal processing is within the state-of-the-art. For the second approach the signal processing, if done digitally, consists of the synthesis of 8N filters, each filter requiring 4N multiplications. These multiplications would have to be performed in N/prf for operation in real time. For N = 50 , and prf = 400, we have 600,000 multiplications per second per gate. Since ten million multiplications per second is reasonable, 16 gates could be processed at once. If each gate were one mile in depth, it would take 12 seconds per beam and about 4 minutes to scan the whole storm with a 2-degree beam.

If the optimum pulse timing (Fig. III-2) were reworked so that the only allowable time increments for the interpulse period were a small negative power of 2 (say, 1/64) of the reciprocal of the smallest interpulse period, then there would be only 16 possible values for all the sines and cosines involved and the number of multiplications would be 32N instead of 12,800N. The 32N multiplications would be performed and all filters built from sums of differences of these terms.

*Andreasen, "Linear Arrays with Variable Inter-element Spacing," IRE Trans. Antennas Propag. AP-10, 137 (1962).




51-ELEMENT ARRAY SYNTHESIZED WITH DIGITAL COMPUTER

| Arrays | Array Length in Wave-lengths | Average Spacing in Wavelengths | | $Z_0$ | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ | $Z_5$ | $Z_6$ | $Z_7$ | $Z_8$ | $Z_9$ | $Z_{10}$ | $Z_{11}$ | $Z_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial Array | – | 3.0 | – | 0.0000 | 0.0207 | 0.0414 | 0.0643 | 0.0869 | 0.1098 | 0.1346 | 0.1614 | 0.1903 | 0.2215 | 0.2546 | 0.2899 | 0.3250 |
| Synthesized Array | 159.5 | 3.19 | 1.50 | 0.0000 | 0.0229 | 0.0417 | 0.0636 | 0.0869 | 0.1098 | 0.1346 | 0.1610 | 0.1906 | 0.2222 | 0.2537 | 0.2399 | 0.3250 |

| Arrays | $Z_{13}$ | $Z_{14}$ | $Z_{15}$ | $Z_{16}$ | $Z_{17}$ | $Z_{18}$ | $Z_{19}$ | $Z_{20}$ | $Z_{21}$ | $Z_{22}$ | $Z_{23}$ | $Z_{24}$ | $Z_{25}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial Array | 0.3622 | 0.4017 | 0.4408 | 0.4844 | 0.5280 | 0.5754 | 0.6273 | 0.6792 | 0.7330 | 0.7909 | 0.8530 | 0.9233 | 1.0000 |
| Synthesized Array | 0.3622 | 0.4020 | 0.4421 | 0.4870 | 0.5280 | 0.5777 | 0.6276 | 0.6792 | 0.7336 | 0.7915 | 0.8536 | 0.9227 | 1.0000 |

Fig. III-2. Filter response for staggered repetition rate. From Andreasen.

# APPENDIX IV

## DETECTING SEVERE CONVECTIVE STORMS AND TORNADOES

Frequencies in the L-band are not usually thought of as being appropriate for weather observations because of the relatively long wavelength and the $1/\lambda^4$ dependence of scattering cross section on wavelength. Thunderstorms associated with the tornado that struck Worcester, Mass. on 9 June 1953 produced strong echoes on a relatively low-powered, small-aperture, L-band MTI radar (modified TPS-1D) located at the Lexington Field Station (see Fig. IV-1). The range marker rings are at 25 and 50 miles. The apparent shadowing behind some of the stronger echoes is a result of saturation and slow recovery of the video circuits. The same storm was observed with an S-band radar located at Lincoln Laboratory. In Figs. IV-2 and IV-3, the hook echo sometimes associated with tornadoes is shown WSW of the radar location at a range of a little over 30 miles. Range marker rings are at 10-mile intervals in these PPI pictures.

Tornadoes offer a special challenge to surveillance. Born in strong convective thunderstorms, they can cut a narrow path of total destruction when in contact with the ground, then lift and travel miles before contacting again. Radar observations of storm cloud systems when tornadoes have occurred often show the hook-like echo formation. Much of the tornado surveillance is done in the middle and southern sections of the United States with ground-based weather radars, with forecasting being done at ESSA's National Severe Storms Forecast Center, Kansas City, Mo. It is possible to identify areas about 100 miles wide by 250 miles long where weather conditions indicate a high probability of tornado generation.

Airborne reconnaissance can fill existing gaps in ground coverage and can provide special high level observations of unusual formations. The radar system that can do a first-rate job of hurricane surveillance will be useful for spotting tornado-generating weather conditions.

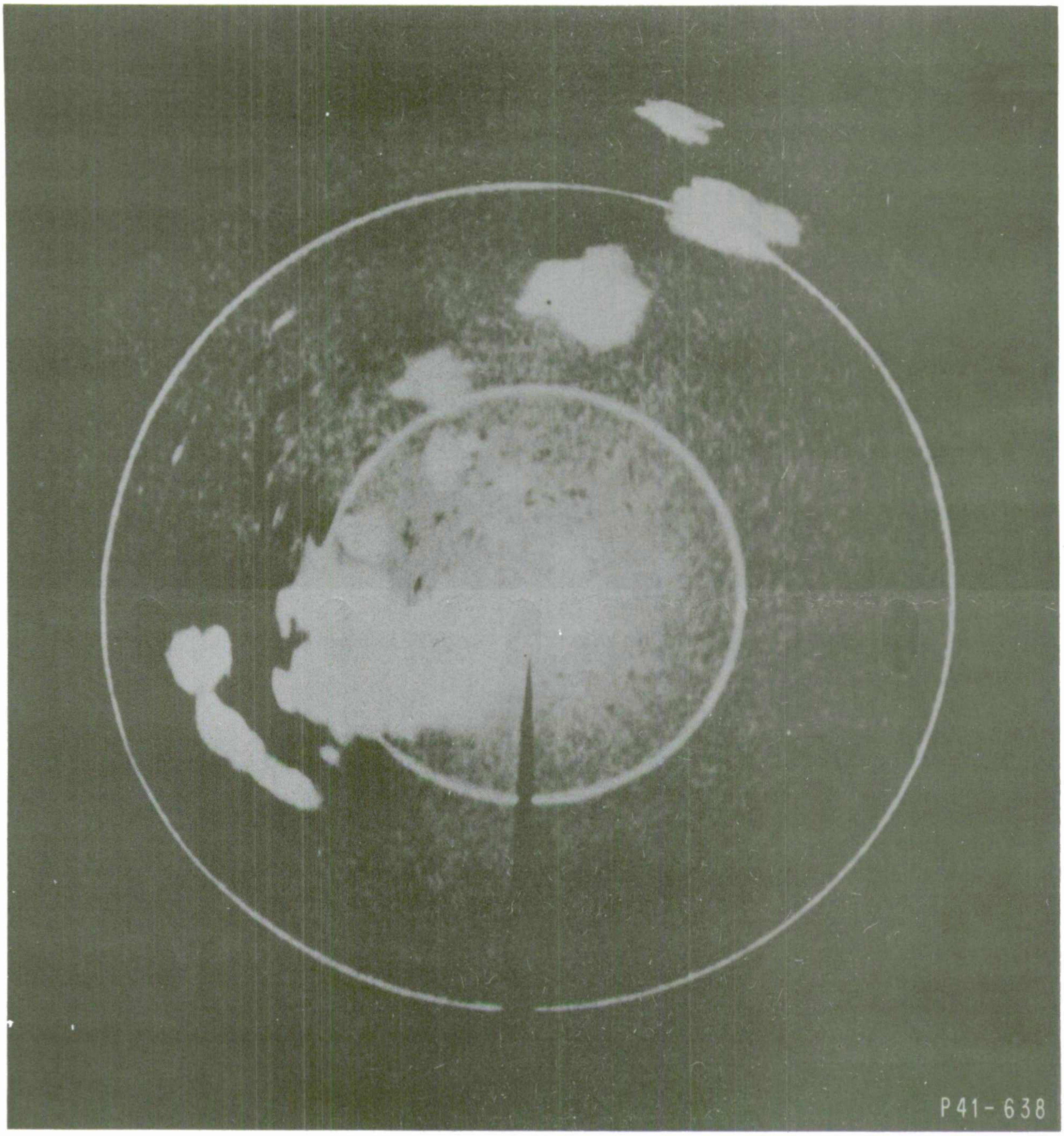



Fig. IV-1. Storms associated with Worcester tornado of 9 June 1953 as displayed on modified TPS-1D radar installed at the Lexington Field Station. MTI operation; L-band; 25- and 50-mile range rings. Time: 1710 EDT.

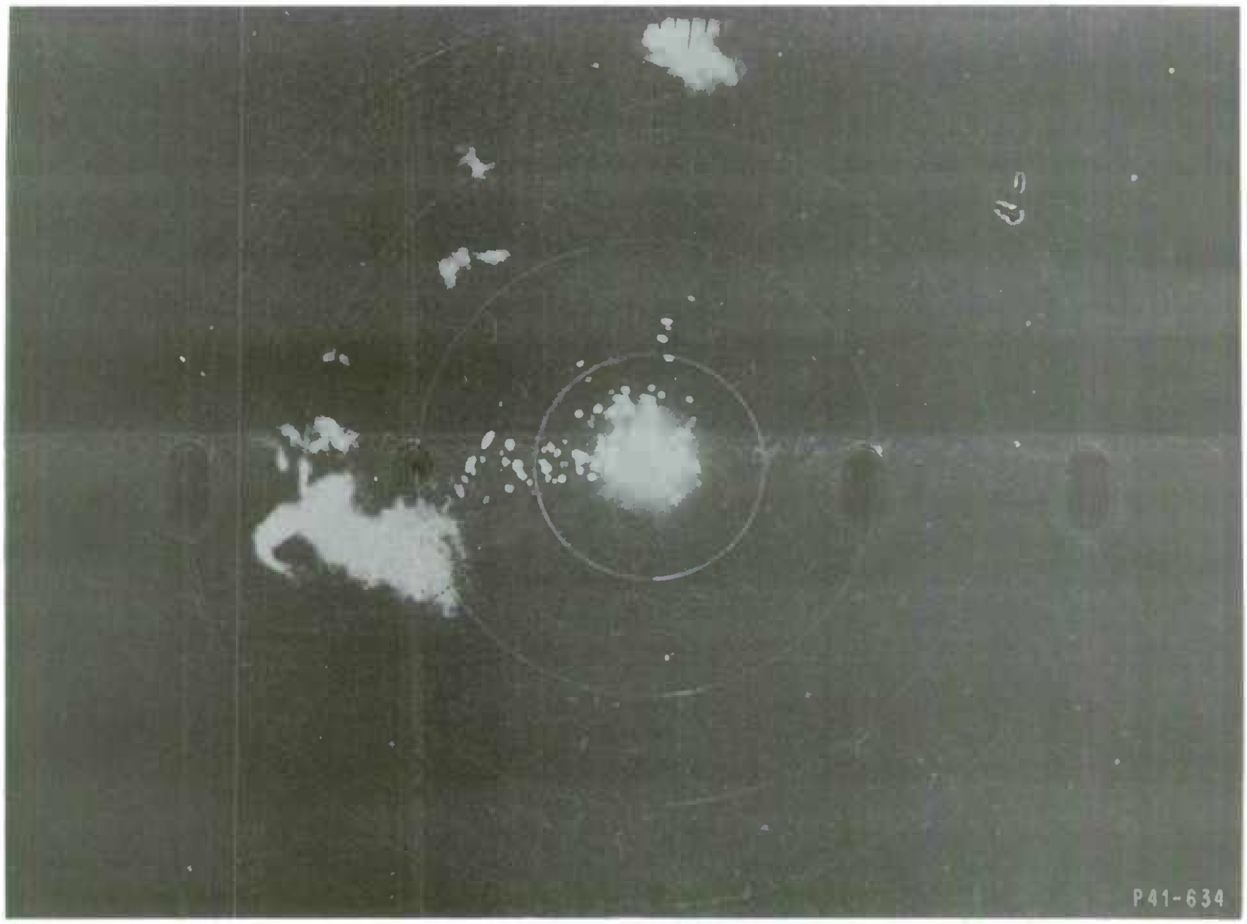



Fig. IV-2. Hook echo associated with Worcester tornado of 9 June 1953 as displayed on developmental S-band radar installed at Lincoln Laboratory. Non-MTI operation; range rings at 10-mile intervals. Time: 1655 EDT.

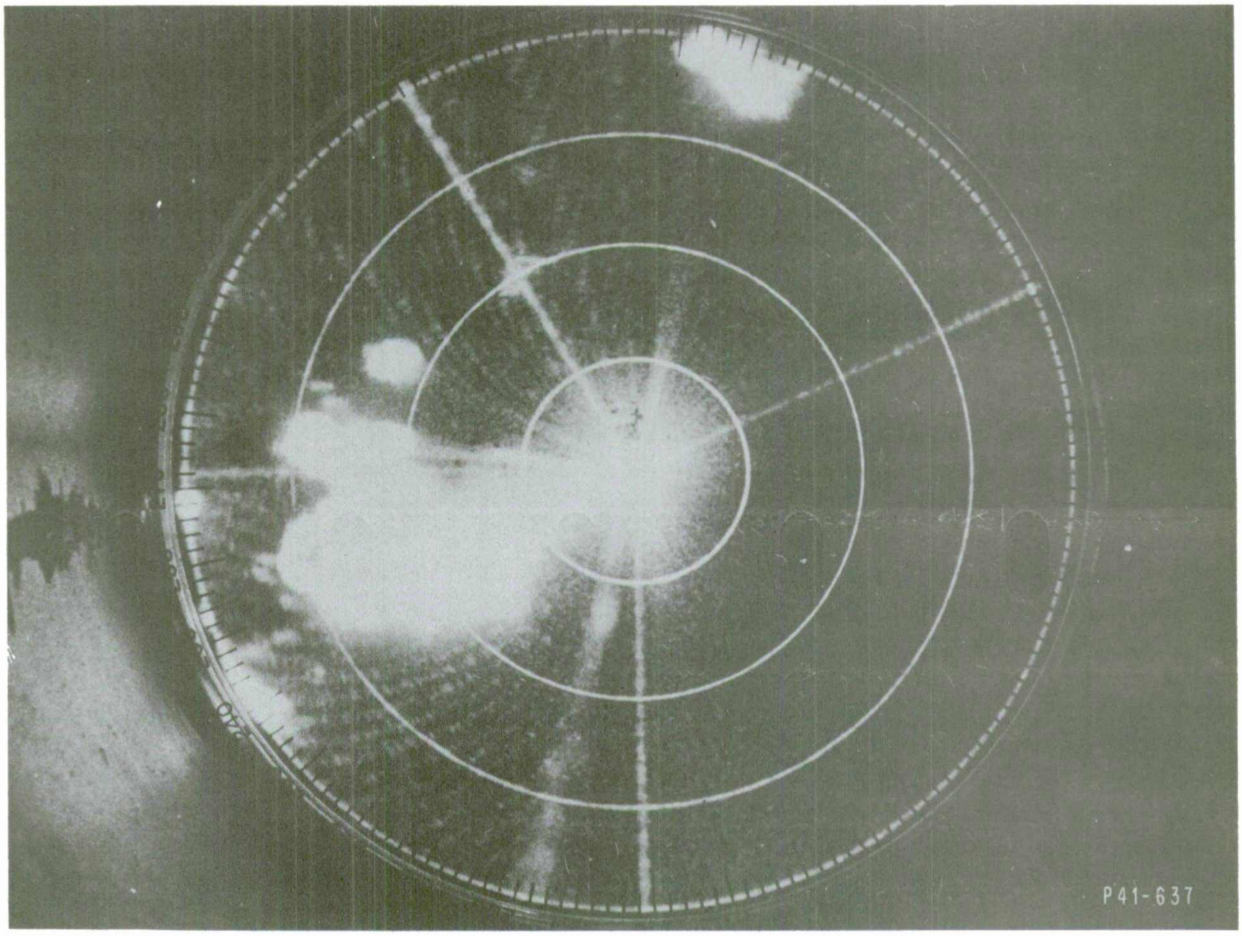



Fig. IV-3. Storms as viewed on S-band radar. MTI operation. Superimposure of 10 complete PPI scans done at 4 rpm. Time: 1701 EDT.

## DOCUMENT CONTROL DATA – R&D

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY *(Corporate author)*<br>Lincoln Laboratory, M.I.T. | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP<br>None |

3. REPORT TITLE
Report on a Weather Radar Study for Aerospace Instrumentation Program Office (ESSI), Electronic Systems Division

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Technical Note

5. AUTHOR(S) *(Last name, first name, initial)*
Meyer, James W., Editor

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| 5 February 1970 | 76 | 15 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO. AF 19(628)-5167<br>b. PROJECT NO. 649L<br>c.<br>d. | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>Technical Note 1970-5<br>9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*<br>ESD-TR-70-7 |

10. AVAILABILITY/LIMITATION NOTICES
This document has been approved for public release and sale; its distribution is unlimited.

| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY |
|---|---|
| None | Air Force Systems Command, USAF |

13. ABSTRACT

Presented here are the conclusions and recommendations of an ad hoc study group which investigated the problems and opportunities of providing improved airborne severe storm reconnaissance with special emphasis on airborne radar detection and surveillance of hurricanes. Study group recommendations are made in terms of what can and should be done in three epochs: by the 1970 hurricane season, by the 1971 hurricane season, and by the 1972 hurricane season. Several options are listed to allow some flexibility in choice of implementation. Discussion of the rationale is also included, and suggestions of desirable improvements in areas other than radar are made. A rudimentary radar hurricane model is presented to aid in the analysis of competing systems, and the implications on radar design of the radar requirements as presented are discussed. Throughout our deliberations we recognized the urgency of implementation of an improved radar and the constraints thereby imposed, but also saw the need of a more pervasive review by a group consisting of members from the government agencies, from the operational units, and from the several scientific and technical disciplines that should be involved in the development of national resources for improved severe storm reconnaissance, analysis, and forecasting.

14. KEY WORDS

| | | |
|---|---|---|
| airborne weather reconnaissance | meteorology | violent storms |
| radar study | hurricanes | rainfall detection |





plt-1800