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FAA TECHNICAL CENTER LETTER REPORT

THUNDERSTORM TURBULENCE DETECTION WITH PULSE DOPPLER RADAR

by

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1. INTRODUCTION.

1.1 PURPOSE.

The purpose of this project is to determine if a pulse Doppler radar can detect the turbulence associated with thunderstorms and provide turbulence warnings to aircraft in airport terminal areas.

1.2 BACKGROUND.

Thunderstorms are a major problem to the safe and efficient movement of aircraft. Inadequate warning of thunderstorm hazards often results in aircraft encountering dangerous conditions. In attempts to avoid the hazards, en route aircraft are sometimes diverted hundreds of miles, while in terminal areas landings and takeoffs are delayed. This causes disruptions in operations and increases fuel and other costs.

Some information on thunderstorm hazards is presently available through radar measurements of precipitation intensity. However, after many years of research, conducted primarily by the National Severe Storms Laboratory (NSSL) (references 1 and 2), it has been determined that precipitation intensity alone cannot be relied on to identify turbulent areas.

Doppler radar techniques offer the potential for determining where turbulent areas are in thunderstorms through measurement of precipitation particle movement. The most promising means is by measurement of the Doppler velocity variance, which is related to small-scale wind variability, i.e., turbulence within a pulse volume. The mean Doppler velocity, which shows large-scale wind variability from pulse volume to pulse volume, may also be related to the production of turbulence. Finally, the precipitation intensity, i.e., radar reflectivity factor, provides a measure of overall storm intensity and reliably identifies damaging hail (reference 3).

The Massachusetts Institute of Technology (MIT) Lincoln Laboratory, under Inter-Agency Agreement DTFA01-80-Y-10546, has cooperated in the establishment of a test bed at the Federal Aviation Administration (FAA) Technical Center, Atlantic City Airport, New Jersey. This consists of a pulse Doppler radar and peripheral equipment to observe, process, display, and record the Doppler information, and an instrumented aircraft to measure and record turbulence concurrently with the radar observations.

Data were collected in 1980 and 1981. Data collection will continue in 1982 and 1983.

This report describes the test bed, the radar and aircraft turbulence measurements, and presents results from the 1980 data collection.

1.3 SYSTEM DESCRIPTION.

The turbulence measurement instrumentation block diagram is shown in figure 1. The system is installed in the Center's Terminal Facility for Automation and Surveillance Testing (TFAST). The pulse Doppler instrumentation radar is one channel of a standard dual channel airport surveillance radar (ASR)-8. A parabolic 15-foot

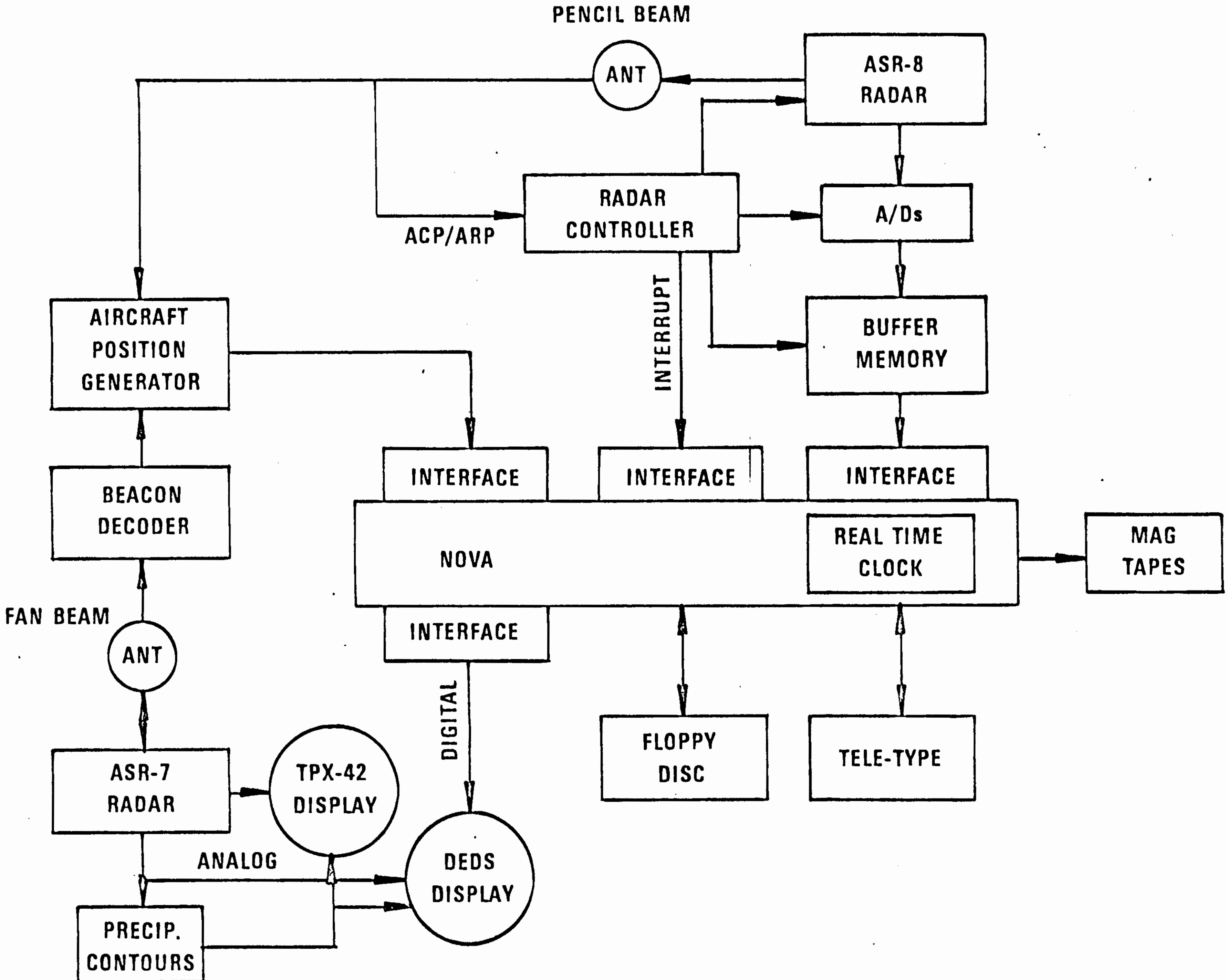

FIGURE 1. TURBULENCE MEASUREMENT INSTRUMENTATION

antenna is interconnected through a waveguide switching arrangement, which allows the ASR-8 to operate with either its standard search antenna or the pencil beam antenna. In this latter configuration, peak power is 1 megawatt, frequency 2790 megahertz (MHz), pulse repetition frequency (PRF) 1030 pulses per second (pps), pulse length 0.6 microseconds (μs), and one-way antenna beamwidth 1.6°.

The station-keeping radar is a standard ASR-7 airport terminal radar. Associated with it is an Air Traffic Control Radar Beacon System (ATCRBS) equipped with a beacon decoder that provides the test aircraft's position to the NOVA computer. The ASR-7 and beacon information is shown on two displays. One is associated with the air traffic control TPX-42 system and shows beacon targets with altitude and identity tags. The second is the Data Entry and Display System (DEDS) which shows the beacon track of the test aircraft and a wedged-shaped data window from the ASR-8 instrumentation radar. The approximately 10 x 10-nautical mile (nmi) data window is configured in the thunderstorm area and the aircraft directed to fly through it. Fields of precipitation intensity (radar reflectivity factor in terms of dBZ), Doppler mean velocity, and velocity variance in terms of $\mathcal{E}^{1/3}$ (cube root of the turbulence dissipation factor - discussed later) may be displayed in the window. These values are used to help select areas for data collection and to reject areas likely to be too hazardous. Figure 2 illustrates how data are collected.

The TPX-42 and DEDS displays show any two of six levels (contours) of precipitation intensity processed from the ASR-7 signals (reference 4). Also, the Video Integrator and Processor (VIP) contours from the local National Weather Service WSR-57 radar have been remoted to the TFAST building and are shown on a separate display. The ASR-7 and VIP contours are used to select thunderstorms for data collection.

The radar controller unit was designed and built by Lincoln Laboratory. It generates triggers, gates, and pulses for the radars and beacon transmitter. It controls the size of the data window, generates commands to the two 10-bit analog to digital converters (A/D's) to digitize the I and Q signals, and controls their transmission to the buffer memory. Periodic interrupt commands are sent to the NOVA to signal when data taking commences and ceases.

The buffer memory has a capacity of 262K twenty-one bit words. It is filled with A/D output data as the antenna sweeps the window. About 200 pulses are used for each range gate resulting in an azimuth resolution of 1.2° (two-way beamwidth).

The number of range gates per azimuth interval can be varied to produce the window dimensions desired. A small number of range gates per 1.2° azimuth interval provides a window with a wide azimuth dimension over a small range extent, while a large number results in a window with a narrow azimuth swath over a larger range interval.

After the antenna sweeps the window, the radar controller unit returns the antenna to the original position (or a new one) to await another sweep command. The NOVA 1200 computer then orders the transmission of radar I and Q digital messages from the buffer memory to the magnetic tapes. Aircraft beacon reports are also processed, digitized, and stored on tape. The fields of radar reflectivity factor, Doppler mean velocity, and $\mathcal{E}^{1/3}$ are generated by the NOVA for display in the window. Cycling time between scans is normally about 80 seconds. The floppy disc and teletype are software interface devices.

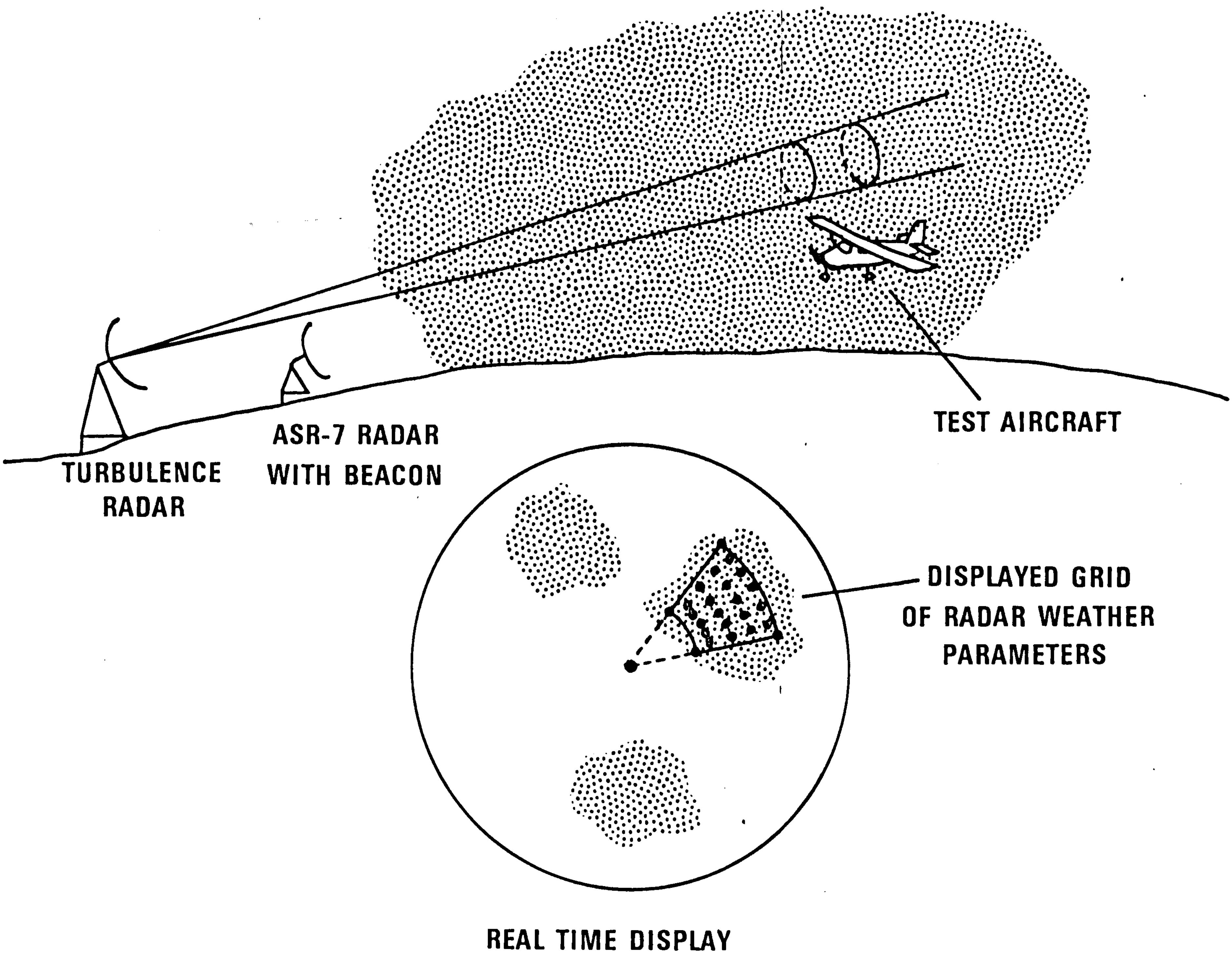

FIGURE 2. DATA COLLECTION GRAPHIC

1.4 AIRCRAFT EQUIPMENT.

A Grumman Gulfstream-I twin-engine turboprop aircraft was instrumented to provide data for turbulence measurements. In 1982, a Convair 580 twin-engine turboprop aircraft will be used. Instruments and data rates are:

a. Altitude transducer (1/sec)
b. Differential pitot pressure (airspeed) transducer (100/sec)
c. Air temperature (1/sec)
d. Center-of-gravity (CG) accelerometer (20/sec)
e. Litton Inertial Navigation System (INS) latitude/longitude (1/sec)
f. Crystal-controller clock (1/sec)

The data are recorded in the aircraft on a Kennedy model 9832 digital tape recorder.

2. TEST PROGRAM.

2.1 GENERAL.

Data are mostly collected during the summer months. The aircraft is launched when thunderstorms are occurring within 40 nmi of the radar (40 nmi is the practical limit for adequate pulse volume resolution with the instrumentation radar). The National Weather Service WSR-57 radar VIP level 3 and 4 storms (41-46 dBZ heavy, and 46-50 dBZ very heavy, respectively) are preferred. VIP level 5 and 6 storms are avoided because of the high probability of damaging hail.

In the 1980 and 1981 data collection programs, the aircraft was flown in an altitude block of 3,000 to 5,000 feet mean sea level (m.s.l.) to avoid encroaching on the New York air route traffic control center airspace. In 1982 and 1983, some higher altitude flights are planned through advance coordination with the New York Center.

The ASR-8 instrumentation radar window is placed in the storm of interest and the aircraft directed to fly on paths that would intercept high values of $^{1/3}$ (turbulence measurement). The altitude of the window is set at window midrange to coincide with the aircraft's planned flight altitude. Occasionally, radar data are taken 1,000 feet above and below the mean altitude to obtain vertical shear information.

2.2 RADAR MEASUREMENTS.

Raw radar I and Q components for each range-azimuth cell (pulse-volume) in the data window are recorded range sequentially. These are then reordered in azimuth and a maximum entropy estimation of the autocorrelation lags made for each pulse-volume, using 204 I and Q components. The autocorrelation lags are used to compute the precipitation intensity (radar reflectivity factor — dBZ), the Doppler mean velocity, and the Doppler velocity variance through specific pulse pair algorithms (reference 5).

The velocity variance, σ_v^2 is related to the dissipation factor, $\mathcal{E}$, by the following equation (reference 5):

$$\sigma_v^2 = 1.828\ (\mathcal{E}a)^{2/3} \tag{1}$$

where:

σ_v^2 = velocity variance (cm^2/sec^2)

$\mathcal{E}$ = dissipation factor (cm^2/sec^3)

a = 2-way Gaussian half-power beamwidth (cm)

1.828 = known constants (assuming isotropic and homogenous turbulence)

thus,

$$\mathcal{E}_r^{1/3} = \frac{\sigma_v}{1.352\ a^{1/3}}\ (cm^{2/3}sec^{-1}) \tag{2}$$

Where σ_v is the Doppler spectrum width. Since "a" is function of range, $\mathcal{E}^{1/3}$ is essentially a range-weighted spectrum width and, as such, should be superior to spectrum width as a turbulence measure.

The dissipation factor (reference 6) represents the kinetic energy converted to heat per unit mass per unit time as larger eddies decay into progressively smaller eddies. The system is steady-state in the inertial subrange (wavelengths about 1 cm to 1 km) where atmospheric motions are isotropic. Most gusts which produce turbulence in aircraft are included within this range. $\mathcal{E}^{1/3}$ rather than $\mathcal{E}$ is used as a turbulence measure because it is directly proportional to the root mean square (rms) vertical acceleration experienced by an aircraft (reference 6) as well as to the Doppler spectrum width or velocity variance (equation 1).

Equation 2 is valid for the inertial subrange if the turbulence is isotropic and homogeneous within a pulse volume, the raindrops move with the wind, and there is no wind shear. Except for wind shear, these conditions are substantially met by restricting measurement range and observing at low elevation angles. Wind shear broadening of spectrum width can, in principle, be removed by measuring the mean velocity in adjacent pulse volumes and subtracting out the effect.

2.3 AIRCRAFT MEASUREMENTS.

Three measures of turbulence are derived from the aircraft instrumentation:

a. Derived equivalent gust velocity, U_{de}, (reference 7). U_{de} is based on unsteady lift theory and has been used by aircraft designers to predict maximum acceleration to be expected from vertical gusts. U_{de} values are computed each 0.1 second from two preaveraged incremental normal accelerations. The peak value (positive or negative) is extracted each second for running 7-second periods.

b. $\mathcal{E}_a^{1/3}$, derived from the average of the square of differences between successive incremental normal accelerations, i.e., the acceleration structure function (reference 5). $\mathcal{E}_a^{1/3}$ is computed from 0.25-second preaveraged acceleration (5 values) by continuously averaging over a 7.5-second interval using a cosine squared weighting. $\mathcal{E}_a^{1/3}$ values are produced each second.

c. $\mathcal{E}_p^{1/3}$, derived from the average of the square of differences between successive airspeed (pitot pressure) measurements, i.e., the airspeed structure function (reference 5). $\mathcal{E}_p^{1/3}$ is computed from 0.2-second preaveraged pitot pressures (20 values) by continuously averaging over a 7.5-second period using a cosine squared weighting. $\mathcal{E}_p^{1/3}$ values are produced each second.

$\mathcal{E}_a^{1/3}$ and $\mathcal{E}_p^{1/3}$ are highly correlated. For a flight made on July 17, 1980, when the aircraft made several penetrations of a VIP level 4 thunderstorm, the correlation coefficient was 0.93. This was based on 497 independent consecutive 7-second data points (2/3 kilometer (km) air travel). For a flight made on July 16, 1980, when the aircraft made penetrations of VIP level 3 thunderstorms, the correlation was 0.91 for 521 data points. Both regression line slopes were approximately 0.75, which is consistent with MacCready (reference 6) who showed that turbulence energy measured by an aircraft longitudinally should be three-fourths of that measured vertically.

The two aircraft turbulence measurements were combined for further analysis, by the following equation:

$$\mathcal{E}_{ap}^{1/3} = \sqrt{\frac{\mathcal{E}_a^{2/3} + (1.333\mathcal{E}_p^{1/3})^2}{2}} \tag{3}$$

3. DATA ANALYSIS.

3.1 PRELIMINARY RESULTS FROM THE 1980 DATA COLLECTION.

Plots of corresponding 1-second values of aircraft and radar turbulence showed a basic relationship between the two turbulence measures (references 8 and 9). This was illustrated more clearly by filtering the two data sets with a Gaussian-shaped filter which removed high frequency components. The result was a close match-up in the major sequences of turbulence. However, the correlation coefficient between the unfiltered data sets was only about 0.5. The low overall correlation is considered to be due to several factors: (a) the aircraft more realistically measures the actual turbulence fluctuations, (b) the occurrence of non-Gaussian Doppler spectra and deficiencies in the pulse-pair algorithm produce errors in radar processing, (c) broadening of radar spectra due to wind shear, (d) errors resulting from interpolation of radar values along the aircraft track between the 80-second radar scans.

Further analysis of the 1980 data along more practical lines was the classification of aircraft and radar-measured $\varepsilon^{1/3}$ into turbulence categories (references 8 and 9). The aircraft classification was determined by relating aircraft $\varepsilon^{1/3}$ to peak U_{de} which has long been used as a turbulence measure (references 2 and 10).

The radar classification was achieved by choosing radar categories to provide a good discrimination between the classes of turbulence. The results showed that almost all radar values less than 4.5 (classified as light turbulence) were associated with negligible or light aircraft turbulence. About 85 percent of the radar values between 4.5 and 7 (classified as moderate turbulence) were associated with light and moderate aircraft turbulence. Radar $\varepsilon^{1/3}$ values equal to or greater than 7 (classified as severe turbulence) were mostly associated with moderate and severe aircraft turbulence (about 75 percent). This latter relationship was significantly enhanced when the radar reflectivity factor (precipitation intensity) was 35 dBZ or greater.

3.2 SPECIFIC PROJECT ACTIVITIES.

Additional data analysis is required to obtain more statistically reliable results. The primary object of this analysis is to:

a. Develop a grand summary of the aircraft/radar relationship that will show whether or not useful turbulence advisories can be derived from radar measurements. This will be done first with 1980/1981 data, later with 1982 data. A total summary will be prepared as indicated.

Intermediate items related to the grand summary are:

b. Refine the tentative aircraft and radar $\varepsilon^{1/3}$ turbulence categories by consideration of additional 1980, 1981, and 1982 data.

c. Investigate in more detail data filtering techniques, particularly COS^2 filtering of radar data similar to aircraft data filtering, and Gaussian overlap/add filtering. Assess practicality of filtering radar data in realtime to produce turbulence advisories.

d. Conduct further research into the use of radar reflectivity factor as a screening parameter in making turbulence estimates with the radar.

e. Assess radar data interpolation errors using 1980 and 1981 data by comparing the relationship between aircraft and radar turbulence for radar data within 20 seconds of radar scan time and more than 20 seconds from scan time. If results indicate errors are significant, decrease radar scan interval to 40 seconds in some 1982 data collections and analyze and compare with previous results.

f. Compare the accuracy of radar measurement of turbulence when the Doppler spectrum width is determined by both the Fast Fourier Transform (FFT) and pulse-pair methods. Requires additional software. (This is a lower priority item since real-time processing will probably require pulse-pair processing.)

g. Investigate wind shear broadening of the Doppler spectrum width and its relationship to the accuracy of radar measurements of turbulence. Requires special data collection to obtain vertical shear information using radar only (no aircraft). Requires additional software. (This is a lower priority item since other studies indicate wind shear effects are not significant).

These project activities are summarized in table 1.

4. PROPOSED CONCLUSIONS AND RECOMMENDATIONS.

It will be concluded that the ASR-8 or comparable pulse Doppler radar can or cannot provide turbulence warnings to aircraft in airport terminal areas. If results are favorable, recommendations for possible field application will be made.

5. ORGANIZATIONAL RESPONSIBILITIES.

All of the tests to be performed under this project will be accomplished by the Systems Test and Evaluation Division, ACT-100H.

6. SCHEDULE.

Project Plan Complete	1/82
1982 Data Collection Completed	9/82
Interim Report	11/82
Interim Report	9/83

7. RESOURCES.

Manpower	3 1/2 MY
TFAST	90 hrs
C-580 A/C	20 hrs
Honeywell Computer	80 hrs
Contract Dollars	20 K

TABLE 1. DATA ANALYSIS GRID SUMMARY

Test Purpose	Data Collection	Data Analysis
Establish whether or not Doppler radar surveillance of thunderstorms can provide turbulence advisories for aircraft.	1982 Collection	Develop a grand summary of the aircraft/radar relationship using 1980/1981 data. Compare with a grand summary developed using 1982 data and consolidate as indicated.
Determine validity of the aircraft and radar turbulence categories.	1982 Collection	Check categories initially with 1980/1981 data, later to include 1982 data.
Improve aircraft/radar turbulence correlation through data filtering.	1982 Collection	Compare COS^2 and Gaussian overlap/add filtering. Assess use of filtered radar data in real-time.
Determine validity of radar reflectivity factor as a screening parameter for turbulence estimates with the radar.	1982 Collection	Check results for classes of radar reflectivity factor e.g., >35 dBZ and <35 dBZ.
Determine if radar data interpolation errors significantly degrade the aircraft radar relationship.	2 or 3 missions in 1982 with 40-sec scan interval if required.	Compare aircraft/radar relationship for data pairs within 20 seconds of scan time and more than 20 seconds using 1980/1981 data. If difference significant, take special 1982 data.
Determine if FFT is superior to pulse-pair for Doppler spectrum width.	1982 Collection	Compare aircraft/radar relationship for FFT versus pulse-pair radar $\varepsilon^{1/3}$.
Investigate wind shear broadening of Doppler spectrum width.	2 or 3 data collections in 1982 with radar only.	Calculate wind shear contribution to the Doppler spectrum width and evaluate significance.

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