ESD-TR-71-60

MEASUREMENT OF CLEAR AIR TURBULENCE IN THE LOWER STRATOSPHERE USING THE MILLSTONE HILL L-BAND RADAR*

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INTRODUCTION

Radar measurements of thin turbulent layers in the clear atmosphere have been extensively reported in the literature and have recently been summarized by Hardy and Katz (1969). The majority of the thin turbulent layer detections reported have been for layers in the lower troposphere. Using the high power radar facilities at Wallops Island, Atlas, et al (1966) have detected layers at heights up to the tropopause. In this paper, layer detections at heights above the tropopause are discussed. The detection of layers in the lower 10 km of the stratosphere is made possible by using a radar system which has approximately 10 dB more sensitivity than the Wallops Island radars for the detection of turbulent layers.

The program of radar measurements of thin turbulent layers was undertaken to provide basic information about the structure of scattering layers in the upper troposphere and lower stratosphere for use in the prediction of tropospheric and stratospheric layers for the prediction of troposcatter field strengths. The radar measurements were accompanied by radiosonde soundings. For a limited series of measurements, a U-2 aircraft was also used to probe for turbulent layers.

II. THE RADAR SYSTEM

The radar system used in the measurement program is described in Table 1. This system differs from that typically used for meteorological measurements due to the use of a general purpose digital computer as an integral part of the receiver. The computer is used to detect the radar returns, incoherently average the returns, and to calibrate the receiver system using signals from a noise tube that is fired after each data taking operation, once per transmitted pulse. To improve the target detection capability of the radar, the recorded data consists of the incoherent average of the signal-plus-noise minus the average of the noise. The recorded data for each elevation scan is further computer analyzed to provide incoherent averages of the received signal over 22.5 km horizontal distance interval at a constant height. The results of a series of the horizontal averages at different heights is then assembled into a profile of C_n^{2*} vs height as shown in Fig. 1.

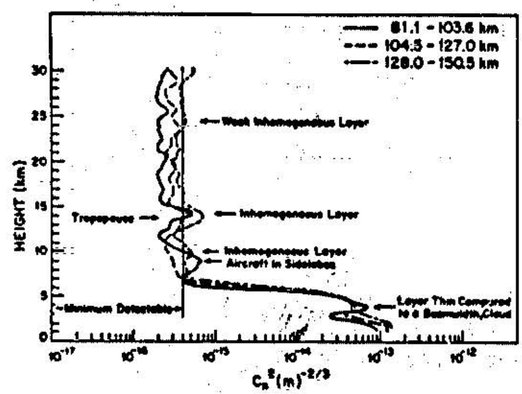

Fig. 1. C_n^2 profiles for 2 August 1968, 1720 GMT, 233° azimuth made using the Millstone Hill Radar.

The corresponding computer generated RHI display is shown in Fig. 2. As an aid in data editing, selected elevation scans are also recorded in the conventional manner by photographing a PPI display. The PPI display that corresponds to the scan used to generate Figs. 1 and 2 is shown in Fig. 3.

The radar system was operated to record data at distances between 80 and 150 km from the radar and heights between 5 and 30 km. At 100-km range and at the elevation angles used, the effective integration volume of the radar is approximately 1.1 km in height, 1.1 km in horizontal distance normal to the plane of the radar and scattering volume and 1.5 km in horizontal distance in the plane of the radar and scattering volume. The height resolution capability of the radar at 100 km is 1.8 km which corresponds to the 10 dB beamwidth of the antenna. This indicates that thin layers closer together than 1.8 km in height will not be resolved and, for layers thinner

* This work was sponsored by the Department of the Air Force.

* C_n^2 as used here is proportional to the backscatter cross section per unit volume of the scatterers. If the layer consists of homogeneous isotropic turbulence it has the usual meaning (see Ottersten, 1969).

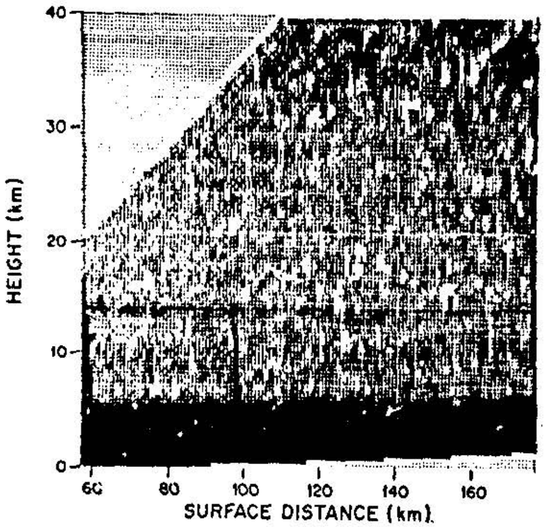

Fig. 2. Computer generated RHI display for 2 August 1968, 1720 GMT, 233° azimuth.

Fig. 3. RHI display for 2 August 1968, 1720 GMT, 233° azimuth made using the Millstone Hill Radar.

than 1.1 km, the measured layer strength will be a function both of the layer thickness and C_n^2. Since most of the layers probed by the U-2 were the order of 100 m thick, it is best to view the layer strength measurements as providing the value of the C_n^2, height product. If the layer at 14 km in Fig. 1 was 100 m thick, the actual C_n^2 value for the 81.1 to 103.4 km average would be 4×10^{-15} $m^{-2/3}$ (2×10^{-16} $cm^{-2/3}$). A homogeneous layer that is thinner than 1 km would have different C_n^2 values reported because the percentage of the beam filled depends upon the distance from the radar. For thin layers the ratios of the measured layer intensities are 1:1.25:1.50 for the 81.1 to 103.4, 104.5 to 127.00, and 128.0 to 150.5 km distance intervals, respectively. The relative magnitudes of the C_n^2 profiles for the layer at 4 km show that, if the layer were homogeneous, it would be thinner than 1 km and the C_n^2 value reported is a lower-bound on the layer strength. Unfortunately, the majority of profile measurements show horizontal variations in layer strengths and estimations of layer thickness based upon this technique are dubious.

The radar system has been calibrated so that the measured C_n^2 value for a layer that fills the beam is within ± .5 dB of the actual value. The stability of the radar and the pulse-by-pulse calibration system used in making the measurements provides a relative rms error of less than ± .1 dB. The major sources of error in making the C_n^2 profile measurements are interference from other radars operating in the same frequency band, reflections from fixed ground targets detected through the side lobes of the antenna pattern and reflections from aircraft detected through the side lobes. Each of these sources of error are monitored during the measurement program. Interference is monitored by the relative magnitude of the variance of the receiver noise temperature which is continuously measured. The 80 - 150 km measurement range was dictated by ground clutter problems. Fixed targets and aircrafts that are detected at ranges between 80 and 150 km must be manually detected using the computer generated RHI displays. Data contaminated either by interference or extraneous targets were rejected.

III. RADAR MEASUREMENTS

The L-band radar used can readily detect turbulent layers with a C_n^2 height product greater than 1×10^{-16} $m^{-2/3}$ km (5×10^{-18} $cm^{-2/3}$ km). Unfortunately a cloud of the same dimension and a Z of 6×10^{-4} mm^6/m^3 for liquid particles or a Z of 3×10^{-3} mm^6/m^3 for ice particles will give the same return. This corresponds to a cloud of liquid particles with a liquid water content the order of 0.005 gr/m^3. The detection of thin turbulent layers is therefore complicated by masking by cloud layers. For this reason, only layers in the clear atmosphere may be detected. Since a single frequency radar is used, auxiliary means must be used to determine if clouds are present. For layers near the tropopause, the presence of cirrus clouds must be determined. The separation between thin turbulent layers and cirrus cloud layers has been made using several criteria. If the layer is detected above the tropopause in a region where the radiosonde data shows a definite lack of moisture, the layer is assumed to be turbulent. If the layer is thin, or the order of the resolution volume of the radar, and is thin throughout the duration of the test, it is assumed to be turbulent. If no cirrus clouds are visually observed by pilots, ground-based observers, and the available TPQ-11 radars at the height of the layer, it is assumed to be turbulent. Whenever doubt existed as to the origin of the radar return, the layer was assumed to be caused by clouds.

Using the above layer detection criteria, the data from 34 days of measurements randomly distributed between January 1968 and August 1968 were examined for the existence of thin turbulent layers at heights above the tropopause. The height of the tropopause was determined using the radiosonde data closest both in time and space to the measurement volume. Two types of layers are reported, persistent and transient. A persistent layer is a layer at a specific height that is present in more than half the elevation scans. The measurements were made by making two elevation scans at a particular azimuth; then moving the antenna to a new azimuth for another set of elevation scans. The azimuth used for the measurements changed from day to day. Typically a series of measurements were made at five separate azimuths spaced over a 180° interval interlaced with a series of measurements at azimuths spaced over a 20° azimuth interval. With the azimuth stepping method used for data taking, a layer had to be present over a range of azimuth values to be classified as persistent.

A series of measurements made on 28 May 1968 are shown in Fig. 4. In this set of data, a

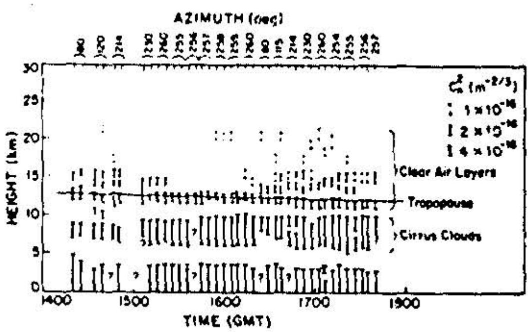

Fig. 4. Radar measured layer structure for 28 May 1968.

persistent layer existed at the tropopause level. The layer at 14 km height is also classified as persistent since it is present in more than half the elevation scans. As shown by the azimuths for which the scans were made, the persistent layers are not confined to a single azimuth sector but are detected at a wide variety of azimuths. These layers cover more than 300 km in horizontal extent. The intensity of the layers, however, change in time and position. The intensity of the layer at tropopause height in Fig. 4 fluctuates in time with approximately a one-hour period. The data on Fig. 4 also shows three transient layers at heights above the tropopause. Again, these transient layers tend to be widespread in horizontal extent but weaker in intensity.

The data for each of the measurement days is presented in Table II. The results are given by day. The data also gives the number of layers per 2.5 km height interval for heights above 10 km and the total number of layers detected above the tropopause for each day. Persistent layer detections are listed in the column with the heading P, transient in the column headed T. The data generally show a layer just above the tropopause. The layer probably is associated with the tropopause but, due to the uncertainty in both the existence and location of a tropopause, it is hard to make a definite judgment about the association between the layer and tropopause position. The feature of the radiosonde profiles most often associated with the layers that occur above the tropopause is a temperature inversion. The association of layer positions with specific Gradient Richardson Number values was not very successful. This most likely is due to the inadequacy of the estimate of wind shear as provided by radiosonde data.

Transient layers have been deteced at heights up to 10 km above the tropopause. The maximum height for a layer detection is 25 km. Weaker layers probably exist above this height but the radar system sensitivity is not high enough to detect them. The transient layers may also appear persistent to a more sensitive radar.

IV. COMPARISON WITH AIRCRAFT MEASUREMENTS

On seven of the measurement days, a U-2 aircraft was flown to probe for clear air turbulence for comparison with the radar measurements. The aircraft used was previously used for clear air turbulence measurements in the Project Hicat Program (Crooks, et al. 1967). The meteorological probes had been removed from the aircraft when we used it. The pilots had, however, been associated with the Hicat Program and had some experience in the "seat of the pants" detection of clear air turbulence.

The aircraft was flown on a radial path from the radar site and slowly sounding in altitude from 10 km to 20 km then down again. The flight path for one of the days is shown in Fig. 5. The

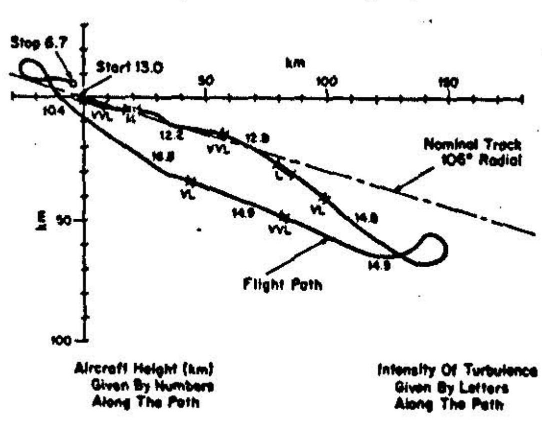

Fig. 5. Flight path of the U-2 relative to the radar site 29 May 1968, 1830-1930 GMT.

numbers listed beside the points along the track give aircraft height. The letters and bars show the extent and intensity of the turbulence. The letter code used is the same as used in Fig. 6. The pilot subjectively recorded the intensity of turbulence with descriptions ranging from very very light to moderate in accordance with the classification procedure previously used for the Hicat Program. No layers more severe than moderate were detected by the aircraft during the measurement program.

Radar measurements were made over a 10° azimuth sector centered about the nominal flight plan radial. Pairs of elevation scans were made in 1° azimuth increments. Radar data for each of the seven flight days together with the radar layer position measurements are shown in Fig. 6. As indicated by the measurements, good agreement exists between the radar measurements and the pilot reports of turbulence. Due to the subjective nature of the pilot measurements, no attempt was made to correlate layer intensity with the pilot reports of intensity. Pilot reports of turbulence with intensities of very light or greater all have radar layers associated with them except for the layer at 18 km on 3 July 1968. The data for 3 June was not computer processed due to a malfunction in the radar site computer. The full sensitivity of the radar system was not available and the lack of a radar layer may be due to the reduction in sensitivity.

A comparison between the aircraft and radar data shows that very very light turbulence as reported by the aircraft is occasionally not detected by the radar. Also several radar layers were detected that were not detected by the aircraft. On June 27, 1968 the detailed layer structure measurements that agree with the aircraft detections was not obtained from the region of space probed by the aircraft. Data from the region probed by the aircraft showed many layers that could not be resolved by the radar resulting in a single layer 7 km thick. Since the layers detected by the radar generally appear to be widespread in horizontal extent and vary in intensity with position and time, it is concluded that agreement was obtained. Data for July 30, 1968 show good agreement between radar data taken along the same azimuth but two hours earlier and after the aircraft run, but poor agreement with the radar data taken at the time of the aircraft flight.

The layers sometimes do not agree exactly in height. On May 29, 1968, the radar layer at 13 km and 18 GMT lies between the two layers detected by the aircraft. From the data, it is uncertain if the layers do agree in position or if the aircraft detected layers lie just above and below the radar layer. The data for July 30 might also be explained by a tendency for the radar layers to be adjacent to the aircraft layers rather than coinciding. Due to the large resolution volume and the thinness of the layers, some of the pilot reports are only 30 meters thick, many of the occurrences of agreement between radar measurements and pilot reports may be for layers in adjacent height intervals rather than layers at the same height.

V. SUMMARY OF RESULTS

The radar measurements of thin turbulent layers show that a layer was detected at or near the tropopause in every one of the 34 sets of measurements made. Layers were detected above the tropopause, in the lower 10 km of the stratosphere, on 31 of the 34 days or 91 percent of the time. The probability of layer detection decreased with height above the tropopause. The layers all appear to be widespread, covering over hundreds of km in horizontal extent. The intensity of the layers vary in time and space with adjacent 22.5 km averages often having significantly different values. The persistence and widespread nature of these layers indicate that they are features of the synoptic weather conditions and their prediction based upon averaged height profiles of temperature and wind may have a chance of success.

Simultaneous aircraft measurements were made for comparison with the radar measurements. For aircraft measurements that indicated turbulent intensities of very light or stronger, a radar layer could be found that occurred at that height and within two hours time and 100 km horizontal distance. Measurements for the same time and horizontal position did not agree as well. The results of a comparison of simultaneous measurements could be explained by the limited height resolution of the radar and by hypothesising that the radar and aircraft layers do not always occur at the same height but often occur in adjacent height intervals. Better radar resolution and instrumented aircraft would be required to verify the hypothesis. Ottersten (1968) has argued that a strong correlation should occur between the radar layers and the aircraft layers. The data tends to support the argument. It may further be argued that as the strongly stable zone in which lower stratospheric turbulence occurs breaks down, only the edges of the turbulent region will be detected by the radar. This argument supports the hypothesis that radar and aircraft layers may occur in adjacent height intervals.

Table 1

Parameters of the Millstone Hill L-Band Radar

Frequency	1.295 GHz (23.2 cm wavelength)
Antenna	84-foot parabola with Cassegrain feed
Antenna gain	47.1 dB
Beamwidth	0.6° between half-power points
Polarization	Right-hand circular transmitted Left-hand circular received
Transmitted power	4 Mw peak (continuously monitored)
Pulse length	10μ sec
Pulse repetition rate	20 per second
Receiver bandwidth	10μ sec matched predetection filter
Data processing	Analog to digital conversion of IF sine and cosine channels every 10μ sec
Detection	Square Law by computer operation
System noise temperature	280°K (includes atmospheric and ground effects averaged over 0-30° elevation angle)
Overall system feed and line losses	1.7 dB
Matched filter processing loss	1.4 dB
Single pulse C_n^2 value for unity signal-to-noise ratio	2×10^{-16} $m^{-2/3}$ (1×10^{-17} $cm^{-2/3}$) at 100 km
Minimum detectable layer C_n^2 value with horizontal averaging and average-noise subtraction	1×10^{-16} $m^{-2/3}$ (5×10^{-18} $cm^{-2/3}$) at 100 km

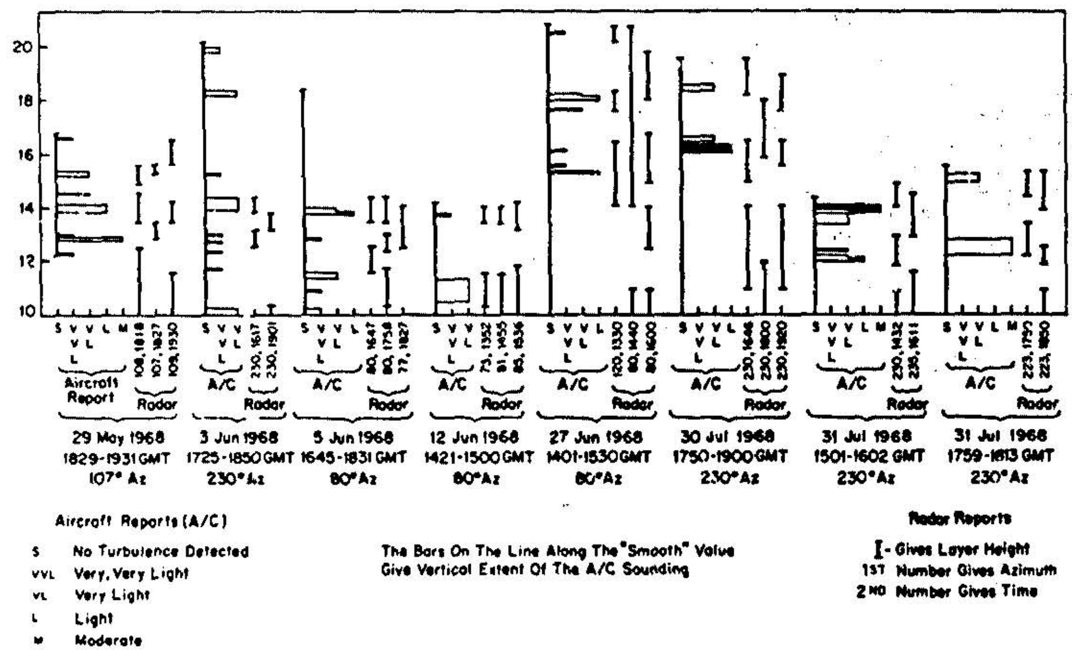

Fig. 6. Comparison between aircraft and radar measurements of clear air turbulence.

Table 2

Turbulent Layer Detections

Date	Time GMT	Max. cloud level	Tropopause Height	Layers above tropopause		Layers from RHI Data: 10 - 12.5 km		12.5 - 15 km		15 - 17.5 km		17.5 - 20 km		20 - 22.5 km		>22.5 km	
1968		km	km	P	T	P	T	P	T	P	T	P	T	P	T	P	T
1/9	1800-2100	6	12.9				1										
1/11	1430-2050	-	11.0		1		1		1								
2/5	1720-2130	2	6.5		1		1										
2/9	1400-2050	6	10.0		1						1						
2/13	1340-1850	6	7.3	1	4	1	1		1				1		1		1
2/19	1810-2100	5	7.6		2		1						1				
3/7	1410-2050	1	9.5		6		1		1		1		1		2		
3/15	1410-1840	8	11.5	1	2		1	1			1						
3/20	1400-2100	10	11.8		2	1			1		1						
3/21	1730-2100	10	12.6		1			1			1						
3/22	1340-1700	10	12.5	1	2			1			1		1				
4/4	1800-2130	12	12.5		1			1			1						
4/15	1330-2120	9	11.5		2	1			1		1						
4/24	1600-1800	9	12.0		1	1			1								
5/8	1310-1900	2	12.7						1								
5/16	1310-1710	9	12.5	1		1		1									
5/20	1440-1830	2	10.5	1	1	1		1			1						
5/28	1400-1950	9	12.5	1	3	1		1			1		1		1		
5/29	1300-2030	11	12.3		5			1	1		2		1		1		
6/3	1410-1950	10	10.4		2	1	1		1								
6/5	1550-1930	9	12.8		1	1		1	1								
6/12	1350-1720	12	14.8		2				1		2						
6/27	1230-1630	11	14.8		3		1			1			1	1			
6/28	1240-1600	8	12.7	1					1	1							
7/29	1430-2020	3	13.8	1	3		1	1		1			1	1			1
7/30	1340-1950	11	12.4		2			1			1		1				
7/31	1230-2020	11	12.8	1	1		1	1					1				
8/1	1330-0100	9	14.5		2		1	1			1		1				
8/2	1400-2020	5	13.8		1			1					1				1
8/5	1220-2030	8	13.1		1				1		1						
8/6	1240-2100	9	14.2		2	1		1			1		1				1
8/7	1230-0100	9	14.4					1									
8/8	1240-2020	7	14.1		2	1	1	1			1		1				
8/9	1300-2020	9	12.6			1	1	1			1						
Total 34	Total of 107 layers detected above 10 km			9	57	12	14	18	13	3	20		14	2	5		4
				66		28*		31		23		14		7		4	

* Total is low due to rejection of any layer with clouds.

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