

# REVIEW OF THE USE OF ELECTROMAGNETIC WAVES AS ATMOSPHERIC PROBES

By E. L. Unthank

Physics Department, University of Melbourne.

(Presented at 39th Congress, ANZAAS, Melbourne  
16-20 January, 1967)

## 1. INTRODUCTION

A title such as this review possesses enables the reviewer to sample the spectrum wherever the whim may take him or wherever his limited knowledge might confine him. I hope that the choice I have made leaves you finally with some doubt as to whether it was dictated by whimsy or necessity.

Recent advances in technology have made more and more of the electromagnetic spectrum available to the atmospheric scientist, to use to his advantage in probing the troposphere and lower stratosphere.

At many stations throughout the world advantage is being taken of these advances both to actively radiate, or probe, into this region, and to passively receive that which originates within the region, so much so that I find it difficult to give a well-ordered or coherent review of the field in a limited time.

## 2. LIDAR

To a gathering such as this, the word coherent must be almost synonymous with laser, and the word laser with lidar, the optical counterpart of the meteorological radar. The recent advent of the laser has made possible a whole new concept of optical probing of the atmosphere. Ligda<sup>1, 2</sup> and Collis<sup>3, 4, 5</sup>, of the Stanford Research Institute, have written at some length on its possibilities and together have carried out much work in developing an operational instrument. Some of the details of their SRI Mark I 1965 Lidar are as follows:

Transmitter:	Ruby crystal laser $\lambda = 6943 \text{ \AA}$
	(3" x 1/4" 90° C axis, Brewster angle ends)
	Q switch
	Pulse length: 24 nano seconds
	Peak power: 10 megawatts
	Prf: 2 per min-maximum
	Beam width 0.03°
	Galilean refractor - 4" aperture
Receiver:	Photomultiplier - 14 stage RCA 7265
	Beam width 0.07° min, 0.8° max
	Bandpass 17 Å

Using this instrument at Norman, Oklahoma, during January 1966, Collis detected a surface haze layer even in (visually) very clear air. The upper level of this layer was closely related to the base of an inversion. He measured cloud base heights and generally found good correlation with conventional radar measurements; however, lidar sometimes gave returns from tenuous clouds which were not detected by microwave radars.

This present SRI lidar has grown from the original model built in 1963 and is of the giant pulse - or so-called, Q switched - type, the most common type in use for meteorological research. In this type of laser the emission of light is suppressed until a given instant when the light energy is emitted as a single short-lived pulse of great intensity, thereby enhancing the range and resolution in range of the instrument.

Fiocco and co-workers<sup>6</sup> have been using lidar since 1963 and have reported detecting optically thin layers at altitudes of about 20 km, between 60 and 90 km and between 110 and 140 km, above Lexington, Massachusetts. In more recent work (Fiocco et. al.)<sup>7</sup> they have attempted to determine the optical thickness and the heights of noctilucent clouds. The results were not conclusive but apparently showed promise.

Gunster<sup>8</sup> reports that the violent turbulence often created downwind of an aircraft carrier has been detected from the USS Enterprise by its scattering of a laser beam.

### 3. CLEAR AIR TURBULENCE

Turbulence in the form of clear air turbulence, CAT, is currently of prime importance to airline companies throughout the world. Collis<sup>9</sup> is not enthusiastic about the prospect of lidar as a means of directly detecting CAT. In fact he states that although it is theoretically possible to detect turbulent inhomogeneities in the atmosphere, it has been shown that the back scattering to be expected from dielectric discontinuities is much too small to be worth serious consideration. However, another part of the electromagnetic spectrum is yielding promising results for the Boeing Company. Lunden<sup>10</sup> and Buhler<sup>11</sup> report that a ground-based, pulsed radar operating at 220 Mhz ( $\lambda \approx 1.35$  m) has shown radar returns from regions in the atmosphere where aircraft have reported turbulence. They consider the frequency range of 100-300 Mhz the optimum for CAT detection. Sufficient positive correlations had been made up till mid-1965 to warrant mounting a similar radar aboard a 727 Jet to carry out flight experiments. The aerial is a long Yagi antenna mounted along the top centreline of the aircraft, producing a fixed 20° beam directly in front of the aircraft. Unlike the centimetre wavelengths, the VHF radar is insensitive to rain and cloud, but detects the refractive anomalies associated with the turbulence.

Yet another approach to CAT, this time with indirect use of electromagnetic waves, is suggested by Hodge<sup>12</sup> whose preliminary study shows a possible relationship between large irregularities of rawinsonde balloon ascensional rates and the presence of CAT. The WF2 and WF44 radars currently in use by the Bureau of Meteorology would yield results of sufficient accuracy to determine irregularities in ascension rates through layers of 2000 to 2500 ft thickness. Hodge found variations greater than 25 per cent from the "normal" in layers of this thickness.

On five separate occasions between February and April 1966 Atlas et al.<sup>13</sup> detected layer echoes from the clear atmosphere <sup>with</sup>  $\pm 0.3$  km of the tropopause using the ultra-sensitive Wallops Island radars. The results at the wavelengths of 71.5 cm, 10.7 cm and 3.2 cm were consistent with the  $\lambda^{-1/3}$  wavelength dependence predicted theoretically (Tatarski<sup>14</sup>) for scatter by a refractively turbulent medium. On at least one of these occasions there were aircraft reports of light CAT at the height of the radar echo. Atlas notes that Zhupaklin had also reported the radar detection of the tropopause in the Soviet Union in 1965.

### 4. METEOROLOGICAL RADAR

The centimetric part of the spectrum is best represented by considering the probing of the atmosphere by means of radars - firstly, those at Wallops Is., doubtless amongst the most powerful in the world.

The 71.5 cm UHF 6 megawatt and 3.2 cm X band 1 megawatt use the same 60 ft aerial, whilst the 10.7 cm 3 megawatt S-band uses a second 60 ft aerial to which can be slaved the UHF-X band aerial to ensure simultaneous search of the same volume. The paper by Glover<sup>15</sup> describing the use of these radar to "lock-on-follow" a single honey bee or a single dragonfly at a range of at least 10 km reads like science fiction, but the results, together with those

recorded in a second paper by Glover<sup>16</sup> and those of Hardy<sup>17</sup> and Konrad<sup>18</sup>, are anything but fiction. In fact, it seems highly probable that they have identified insects and birds as the principal sources of the so-called "dot" angels. (Dot angels are the discrete radar echoes which are observed from highly localized regions of apparently clear atmosphere.) The same conclusion has been reached by Deam and Lagrone<sup>19</sup> on the basis of dual wavelength measurements and even Atlas<sup>20</sup>, who previously postulated rising convective "bubbles" as a possible explanation, reported to the 15th General Assembly of URSI in Munich last year in favour of insects as a principal source. Atmospheric probing simultaneously at two or more wavelengths enables the scientist to extract far more information from the echoes, since scatterers reflect radiation in a manner which is wavelength dependent, ranging from the  $\lambda^{-4}$  of particulate matter in the Rayleigh region to the  $\lambda^{-1/3}$  previously mentioned for clear air inhomogeneities.

Secondly, meteorological radars, particularly those using 10 cm wavelengths, have been widely used in attempts to make quantitative measurements of rainfall over wide areas. This active field of research produced papers at the 12th Conference on Radar Meteorology last year from Cogombles in France, Chernikov and Muchnik in USSR, Chatterjee in India, as well as many authors from America. The papers appeared to be in general agreement that although much progress had been made the accuracy of the method had not been established.

In Australia, the Bureau of Meteorology has been investigating this use of radar for some time and Barclay<sup>21</sup> has already obtained some promising results. A network of recording rain gauges has been set up in the Werribee area to proceed with areal rainfall studies using the Melbourne Weather Radar. In addition, Dr. Eccles, Physics (RAAF), University of Melbourne, is currently instrumenting an experiment to measure side-scatter from rain using the Melbourne Weather Radar as transmitter and a 21 ft parabolic antenna feeding a 10.7 cm receiver as the receiving facility at a field station site near Point Cook - approximately 12 miles from the transmitter. It would appear that an investigation of rain-drop spectra is a necessary adjunct to both of these experiments.

## 5. DOPPLER RADAR

Several workers in the United States are extracting information of drop size spectra from Doppler radar returns and as there appears to be high hopes for significant advances in radar meteorology as a result of the development of these radars, I will comment on them as a third "selection" in the centimetric range of atmospheric probes. The nature of the instrument enables measurements to be made of the velocities of tracers within the pulse volume; thus it is well suited to determining the vertical and rotational motion associated with clouds and thunderstorms. Amongst the Dopplers currently in use in the US are those of Battan, Donaldson, Lhermitte and Rogers; further, Atlas<sup>22</sup> states that a major effort is being mounted in this field by Soviet workers headed by Gorelik and Chernikov.

Battan and Thiess<sup>23</sup> have developed a vertical pointing Doppler operating at 9245 Mhz, 3 cm, 4000 p. r. f. and a maximum developed operating height of 63,000 ft. They term it a "coherent" Doppler because of the memory oscillator (COHO) which is triggered with each outgoing pulse and with which phase comparisons are made for the returned power. In this fashion a phase difference is established between the outgoing and returned power of each pulse and by comparison with that of the next pulse a time rate change of phase - and hence a velocity - is established for the scatterer. Using this instrument they have studied thunderstorms during the past three summers and have made measurements of terminal velocities of particles, updraft velocities and hailstone sizes. The 5.4 cm Porcupine Doppler at AFCRL used by Donaldson, Browning<sup>24</sup> and others has a fully controllable aerial and is usually used in a mode where it rotates around the vertical axis at a fixed angle of elevation. It has been used to measure horizontal wind components and wind shears in thunderstorms. Donaldson is of the opinion that the observed wide spread of the Doppler spectrum is associated with turbulence and hopes to look horizontally at uniform snow in order to make further measurements in this matter in which he is at variance with Battan. Rogers<sup>25</sup> used a 3.2 cm Doppler radar to study Hawaiian rain, to measure updraft velocities (up to 7 m/sec) and drop size distributions and to obtain some information on coalescence processes. Lhermitte<sup>26</sup> has tracked dot angels (insects?) with his Doppler for up to 30 hours, thereby obtaining data from an otherwise clear atmosphere and enabling him to probe the winds in the lowest few kilometres.

## 6. REFRACTOMETERS

Thus far, I have cited a number of techniques currently in use to actively probe the atmosphere at a variety of wavelengths and for a variety of purposes. I wish to conclude by quoting one or two cases in which information concerning the atmosphere is being obtained by what can be termed the passive response of electromagnetic devices to the existing meteorological conditions - these devices, refractometers, measure directly the refractive index,  $n$ , of the atmosphere or more frequently are calibrated to measure the refractivity,  $N = (n - 1)10^6$ . The refractivity is a function of the atmospheric pressure, temperature and partial pressure of water vapour,

$$N = \frac{77.6}{T} \left( p + \frac{4810e}{T} \right)$$

and hence can be calculated from these three parameters as measured by radiosonde. However, the time response of the sonde elements and the sequential sampling technique used in the sonde make this data unsuitable for determining refractivity microstructure of the atmosphere.

Refractometers employ microwave cavities or sampling capacitors which produce resonant frequencies which are proportional to the dielectric constant and hence to the refractive index,  $n \propto \sqrt{\epsilon}$ , of the atmosphere between the plates. Lightweight refractometers of the Hay type<sup>27</sup> (10 Mhz - parallel plate sampling capacitor) or Deam type<sup>28</sup> (400 Mhz - coaxial sampling capacitor) may be balloon-borne, whilst Thompson-Vetter type<sup>29</sup> (9 Ghz - sampling cavity) are usually mounted in aircraft.

In the United Kingdom, Lane<sup>30</sup> has made a series of airborne soundings with a microwave refractometer and rapid-response thermometer in the region of elevated layers in fine and settled weather, and found that approximately 10% of inversions investigated were less than 8 metres in depth. Fukushima et al<sup>31a,b</sup> have made both kytoon and airborne measurements of the spatial variation of refractive index in Japan and found a considerable amount of microstructure. Bull<sup>32</sup> has used spaced cavities mounted on towers to investigate refractive index variations and the contribution of humidity to these variations within 60 m of the ground. The influence of the refractive index structure on "forward" propagation links and on "anomalous" propagation radar echoes has brought workers in these fields together with meteorologists in several parts of the world. In May-June 1966, Lane took his spaced-cavity refractometer to Wallops Island, U.S., to participate in the six-week intensive measurements program in Clear Air Turbulence organized by Katz of Johns Hopkins University and AFCRL. In Australia, Jenkinson and his co-workers of PMG Research Laboratories have made refractometer flights over Bass Strait and tower measurements at Ivy Tanks on the Nullabor to obtain refractivity profiles, to 5000 ft over the Strait and 250 ft on the tower. The results of January 1966 showed clearly the sharp  $N$  gradients associated with a subsidence temperature inversion but the Melbourne Radar showed no anomalous propagation at the same time. Results at Ivy Tanks 14 May 1966 2300 hr have shown conditions of sub-refraction developing between 40 ft and 150 ft above ducting conditions up to 40 ft\*. These resulted from a humidity increase with height+.

The PMG Research Laboratories have received assistance from the Bureau of Meteorology in determining the meteorological conditions producing these profiles and the subsequent effects on the propagation being studied in these areas - namely about 4 Ghz.

---

\* (See Jenkinson<sup>36</sup>)

+ (See van Dijk<sup>37</sup>)

## 7. CONCLUDING REMARKS

It is evident that this review should have included information on active probing such as the use of infra-red techniques in the atmosphere, cloud studies at millimetre wavelengths, one-way propagation studies at all wavelengths to determine atmospheric constituents through absorption and attenuation measurements. It could also have considered the work of Zonge<sup>33</sup> and others in detecting the radiation from growing thunderclouds 10-15 minutes before the first stroke at frequencies up to 100 Mhz, that of Rossby<sup>34</sup> of somewhat similar nature at 610 Mhz and of Atkinson<sup>35</sup> who has detected the radiation emitted by falling raindrops. This is indeed an active field with promise of a very fruitful future.

## Lidar:-

## REFERENCES

1. Ligda, M.G.B. 1964 "Meteorological Observations with Lidar", Proc. of the 1964 Conf. on Radio Met., pp 482-489.
2. Ligda, M.G.B. 1965 "Laser in Meteorology", Discovery, July 1965.
3. Collis, R.T.H. 1966 "Lidar: a new atmospheric probe", Quart. J.R. Met. Soc. 92: 392, pp. 220-230.
4. Collis, R.T.H. 1965 "Lidar Observation of Cloud", Science, Vol. 149. August 1965.
5. Collis, R.T.H. 1966 "Lidar Observations of the Lower Atmosphere", Proc. of 12th Conf. on Radar Met., Norman, Oklahoma, 17-20 Oct. 1966, A.M.S. Boston, pp. 102-103.
6. Fiocco and Smullin 1963 "Detection of Scattering Layers in the upper atmosphere (60-140 km) by optical radar". Nature, Vol. 199, pp. 1275-76.
7. Fiocco and Grams 1966 "Observations of the upper atmosphere by optical radar in Alaska and Sweden during the summer 1964", Tellus, 18:1, pp. 34-38.
8. Gunster 1966 "Practical uses of lasers", Science Journal 2:6, June 1966, pp. 32-45.

## CAT:-

9. Collis, R.T.H. 1966 "Clear air turbulence detection", IEEE Spectrum 3:4 p. 56.
10. Lunden, 1965 "Clear air turbulence radar studies", Boeing Airplane Co. Document No. D6-17722.
11. Buhler and Lunden 1965 "A note on VHF backscatter from turbulence in the upper troposphere", J. App. Met. 4:151-2.
12. Hodge, Mary W. 1966 "Large irregularities of rawinsonde ascensional rates within 100 nautical miles and 3 hours of reported CAT". Report from Systems Development Office, ESSA, Washington.
13. Atlas, D., Hardy, K.R. 1966 "Radar detection of the tropopause and clear air turbulence". Proc. 12th Conf. on Radar Met., pp. 279-284.

14. Tatarski, V.I. 1961 "Wave Propagation in a Turbulent Medium", McGraw Hill, New York.

#### Meteorological Radars:-

15. Glover, K.M., Hardy, K.R., Landry, C.R. and Konrad, T. 1966 "Radar characteristics of known insects in free flight", Proc. of 12th Conf. on Radar Met., pp. 254-8.
16. Glover, K.M. and Hardy, K.R. 1966 "Dot angels: Insects and Birds", Proc. of 12th Conf. on Radar Met., pp 264-268.
17. Hardy, K.R. and Glover, K.M. 1966 "24 hour history of radar angel activity at three wave-lengths", Proc. of 12th Conf. on Radar Met. pp 269-274.
18. Konrad, T.G. and Hicks J.J. 1966 "Tracking of known bird species by radar", Proc. of 12th Conf. on Radar Met., pp 259-263.
19. Deam, A.P. and Lagrone, A.H. 1966 "Quantitative Observations of Dot Angel Echoes at two frequencies", Radio Sci. (formerly J. Research, Sect. D, Nat. Bureau of Std., Washington), 1:5, pp. 537-43.
20. Atlas, D. 1964 Advances in Geophysics, Vol. 10, Academic Press, New York.
21. Barclay, P.A. 1964 "Study of Caboolture storm comparison of radar and rain gauge observations", Proc. 11th Weather Radar Conference. Boulder, Color. Sept. 14-18, A.M.S., Boston.
22. Atlas, D. 1965 "Activities in Radar Meteorology, Cloud Physics and Weather modification in the Soviet Union", Bull. Amer. Met. Soc. 46:11, pp. 696-706
23. Battan, L.J. and Thiess, J.B. 1966 "Observations of vertical motions and particle sizes in a thunderstorm", J. Atmos. Sci. 23:1, pp 78-87.
24. Browning, K.A. 1967 To be published in Quart. J.R. Met. Soc.
25. Rogers, R.R. 1966 "Doppler Radar investigation of Hawaiian Rain", Proc. 12th Conf. on Radar Met., pp. 128-134.
26. Lhermitte, R.M. 1966 "Probing air motion by Doppler analysis of radar clear air returns", J. Atmos. Sci., (Also Proc. 12th Conf. on Radar Met., pp. 295-299).

#### Refractometers:-

27. Hay, Martin and Turner 1961 "Lightweight Refractometer", Rev. Scient. Instrum. Vol. 32, p. 693.
28. Deam, A.P. 1962 "Radiosonde for atmospheric refractive index measurements", Rev. Scient. Instrum. 33:4, pp. 438-441.
29. Vetter, M.J. and Thompson M.C. Jr., 1962 "An absolute microwave refractometer" Rev. Scient. Instrum. 33:6, pp. 656-660.
30. Lane, J.A. 1965 "Some investigations of the structure of elevated layers in the troposphere". J. Atmos. Terr. Phys. 27, pp. 969-978.

- 31a Fukushima, M. and Iriye, H. 1965 "Study of spatial distribution of atmospheric refractivity from aircraft observations" J. Rad. Res. Labs., Japan, 12, pp. 89-102.
- 31b Fukushima, M., and Iriye, H. 1966 "Observations of small-scale irregularities of the radio refractive index in the lower troposphere", J. Radio Res. Labs., Japan, 13:68/69, pp. 201-210.
32. Bull, G. 1966 "Power spectra of atmospheric refractive index from microwave refractometer measurements", J. Atmos. Terr. Phys. 28:5, pp. 513-520.

#### Miscellaneous:-

33. Zonge, K.L. and Evans, W.H. 1966 "Prestroke radiation from Thunderclouds", J. Geophys. Res. 71:6, pp. 1519-23.
34. Rossby, S.A. 1966 "Sferics from lightning within a warm cloud", J. Geophys. Res. 71:16, pp. 3807-9.
35. Atkinson, W.R. and Paluch, I. 1966 "Electromagnetic emission from pairs of water drops exchanging charge", J. Geophys. Res. 71:16, pp. 3811-3816.
37. Jenkinson, G.F. 1967 Proc. IEEE, April 1967.
38. van Dijk, M.H. 1967 Proc. IEEE, April 1967.

#### General References:-

- Masterson, J.E., Karney, J.L. and Hoehne, W.E. 1966 "The laser as an operational meteorological tool", Bull. Amer. Met. Soc., Boston, 47:9, pp. 695-702
- Lhermitte, R.M. 1966 "Application of pulse Doppler radar technique to meteorology", Bull. Amer. Met. Soc., Boston, 47:9, pp. 703-712.