

PROBING THE CLEAR ATMOSPHERE WITH RADAR

Ever since they were placed in use for aircraft detection, radars have detected "angels." An "angel" is a radar reflection from a location in the atmosphere that does not contain a known discrete target. Such reflections have been variously attributed to birds or insects too distant to see by eye, or to local fluctuations in the refractive index of the air. For quite some time heated scientific arguments have taken place in attempts to explain these observations with only limited success.

During the past year, in a series of experiments sponsored by the Air Force and the National Aeronautics and Space Administration, the Applied Physics Laboratory has made great inroads toward a scientific explanation of radar reflections from the clear atmosphere, i.e., an atmosphere in which no substance or target is visible by eye. In essence it was found that birds, insects, and refractive index fluctuations are all detectable by radar, if the radar has the proper characteristics.

In the summer of 1965, the multi-wavelength radar facility constructed at Wallops Island, Virginia, by the Lincoln Laboratories for a re-entry physics program was put into use by APL for the study of atmospheric phenomena principally aimed toward the detection of clear air turbulence.

The basic radar system is composed of three coordinated radars at 3.2, 10.7, and 71.5 cm wavelengths with powers of 1, 3, and 6 megawatts and

beamwidths of 0.2, 0.5, and 2.9 degrees, respectively. The radar antennas are slaved to look in the same direction and all data gates can be slaved to probe the same volume of space within the beamwidth limitations. A photograph of the two 60-foot antennas used for the radar system is shown in Fig. 1. A vast array of displays and methods of

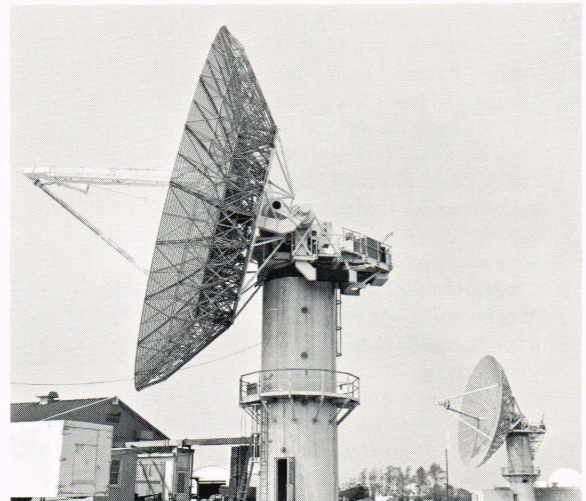


Fig. 1—Two antennas of the multifrequency radar system described in this report. Both dishes are 60 feet in diameter—the closer antenna is used for the 3.2 and 71.5 cm radars and the other is the tracking 10.7 cm radar antenna.

HERE

Recent experiments with high-powered radars have shown that electromagnetic radiation is scattered sufficiently by irregularities in the atmospheric refractive index to use radars as a probe. Photographs of the oscilloscope presentations show unmistakable evidence of convective cells and of horizontally stratified layers in the air. These cells and layers were simultaneously investigated by aircraft specially equipped with refractometers and a direct relationship was found between the position of the reflected radar signals and the region of large variance in refractivity. Some of the experiments also included the detection and tracking of birds and insects with radar. This article discusses these experiments and suggests the future use of radar as a valuable aid in the fields of meteorology and entomology.

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recording are used. As an example, there is an array of eight oscilloscopes for plan-position and range-height presentations.

In this article we will discuss briefly some of the highlights of the series of experiments carried out in this program during the past year. These include tracking of insects and birds dropped from airplanes, detecting the tropopause, and establishing the fact that atmospheric layers and convective cells are detectable by radar on a routine basis. This past year's work will have a significant effect on the future use of radar as a fine-scale meteorological and entomological research tool. More detailed information on the experiments discussed here may be found in the proceedings of a conference held at the University of Oklahoma in October of this year.¹

The Birds and the Bees

Our aim at the start of the experiment was to study scattering from the clear air caused by non-particulate matter, i.e., we wanted to exclude targets such as birds and insects. However, it became evident very soon that there was no technique

available to aid us in discriminating between a reflection from a discontinuity in the atmosphere and a bird or an insect. It was necessary to establish a criterion to help us eliminate discrete objects or particulate matter from true clear-air reflections. Locking on targets of opportunity was unsatisfactory since we had no effective means of identifying the target. We therefore decided to drop known birds and insects from a small airplane and track them.

Insects were readied for our experiment by being fed sugar water, placed in containers, and carried aloft in a small airplane piloted by Roland Masek of APL. Mr. Masek was vectored along a radius parallel to, and in the direction of, the wind. When the airplane was in a position free of chance targets, a single insect was ejected into the airstream. Our radar operators then were able to detect the two targets, airplane and insect, and lock on and track the lone insect. Once in automatic track we could record the flight characteristics of the particular insect. We dropped honeybees, dragonflies, and two species of moths.

Certain features of the flight pattern of the insects may be deduced from the records of radar signal strength. In one pair of experiments we tracked a hawkmoth, Fig. 2, in flight and a second one whose wings were removed to preclude its flying. A comparison of the signal strength (or

¹ Twelfth Conference on Radar Meteorology, American Meteorological Society, University of Oklahoma, Norman, Oklahoma, Oct. 17-20, 1966.

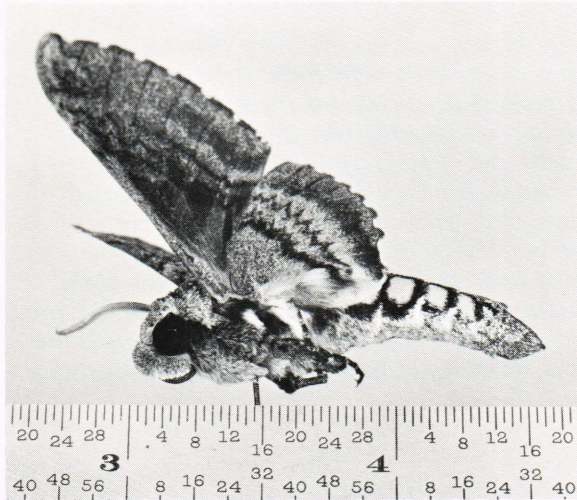


Fig. 2—A hawkmoth similar to the ones described in the text.

radar cross-section) records may be made from the two records shown in Fig. 3. In the upper portion we see records of the winged moth and in the lower portion a similar record from the wingless moth made on the 10.7 cm radar. There are periods in which the cross-section varies relatively slowly by two orders of magnitude over an interval of several seconds while at other times the cross-section is relatively constant. In general, the radar cross-section depends on the size, shape, and moisture content of the insect, whereas the short-term changes resulting in signal fluctuations are a function of the kind of insect, its wing size and motion, and the orientation of the insect's body relative to the axis of polarization. From a study of the trajectory of the moth, we conclude that the large changes in cross-section are not related to the changes in flight path; hence they are attributed to those periods when the moth is flying. The lower record, on the same time scale, shows no corresponding large fluctuations from the wingless hawk moth. Proof of the direct relationship between the exact behavior or wing motion of the insect and radar signal fluctuations is unlikely because of the difficulty in viewing or photographing the insect in free flight at the distances involved in these experiments.

Insect cross-sections at the various radar frequencies also yield important results. At the 3.2 cm wavelength the radar cross-sections of these insects fell between about 0.1 and 1 cm². For the 10.7 cm radar the insect targets were measured to lie between 10⁻³ and 0.5 cm². These cross-sections show a wavelength dependence of λ^{-2} to λ^{-3} . (Because of this sharp dropoff of reflectivity with wavelength the insects were not detected on the 71.5 cm

radar.) The results of these measurements are in good agreement with those of The University of Texas.² It is of interest to note that the 10.7 cm radar is sufficiently sensitive to track the small insects out to a distance of 20 nautical miles.

The bird experiments followed closely along the lines of the insect drops. It was the purpose of the tests to find any distinctive variations in signal received from the bird. If this were successful, we would have a way of discriminating between the desired atmospheric targets and those of birds. Three bird species were dropped—grackle, sparrow, and pigeon. They were dropped at ranges between 8 and 10 miles from the radar.

Although the analysis is still continuing, some spectra are already available showing the fluctuation rate of birds. A sample spectrum for a pigeon on the 3.2 cm radar is shown in Fig. 4. Note the low frequency content of this spectrum. Most of the energy lies in the region below 10 cps. However, it is interesting to speculate on the peak in this spectrum—around 4 cps. There is good reason to believe this is the wing beat frequency. Previous investigators³ have measured wing beat rates of 4.0 and 4.3 cps for a wood pigeon and a rock pigeon, respectively.

Compared with the insects, the birds are, of course, quite large; typical mean cross-sections lie between 1.5 × 10⁻² to 10 cm² with no clear-cut

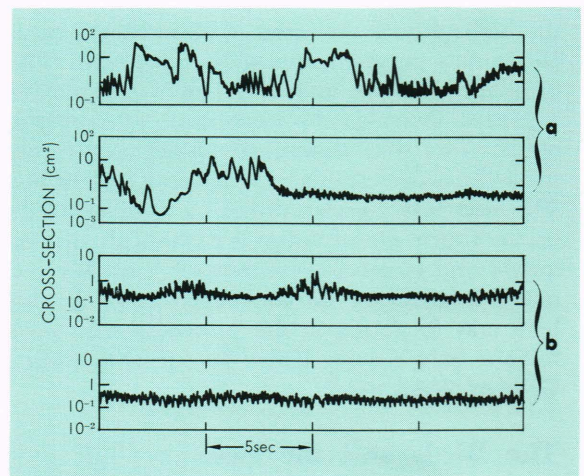


Fig. 3—Signal strength recordings of the return from the hawkmoths: (a) with wings, (b) wings removed.

² R. G. Hajovsky, A. P. Deam, and A. H. LaGrone, "Radar Reflections from Insects in the Lower Atmosphere," *IEEE Trans. Antennas and Propagation*, 14, 224-227, 1966.

³ C. H. Greenwalt, "Dimensional Relationships for Flying Animals," *Smithsonian Miscellaneous Collection*, 144, No. 2, 1-46, 1962.

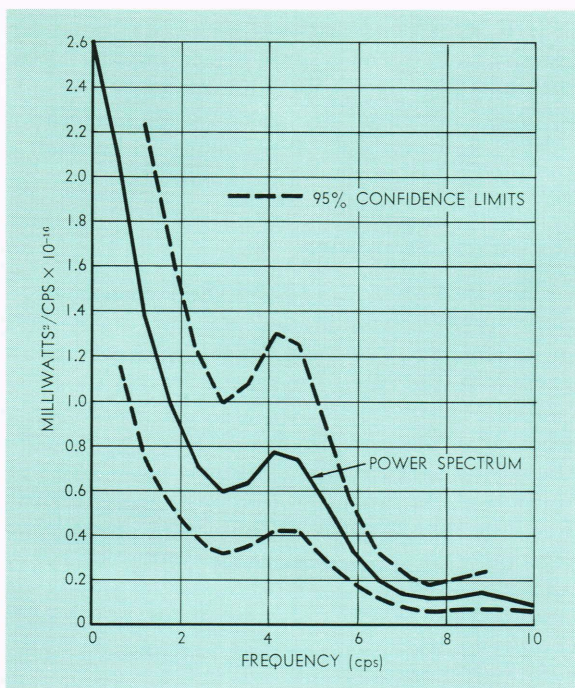


Fig. 4—Power spectrum for a pigeon (X-band).

wavelength dependence. The lack of a wavelength dependence is not surprising considering the fact that birds fall in the “Mie” rather than the “Rayleigh” scattering region.

Rayleigh scattering is that region in which the scattering cross-section of particles, small compared with the wavelength of the electromagnetic radiation, varies as λ^{-4} . For particles roughly the size of the radiation wavelength we find the so-called Mie region in which the scattering cross-section of a particle of given size oscillates about a mean value with change in wavelength.

These experiments have evoked considerable interest among entomologists and ornithologists in that they show a way of studying insects and birds in flight and at altitudes which are beyond the normal techniques available previously.

The Tropopause

The tropopause is a layer of air lying at an altitude of 25,000 to 50,000 feet which delineates the separation between the troposphere (the lowest atmospheric layer) and the stratosphere. It is a region in which the temperature no longer decreases with height as is the case below that level, but either remains constant or indeed increases with increase in altitude. This is the region near which clear air turbulence is found to occur. This turbulence has been given much attention recently



Fig. 5—Helicopter and refractometer package being launched. During measurements the package is suspended in undisturbed air about 85 feet below the helicopter.

because of its adverse effect on jet aircraft operation.

During February and March of 1966 we had equipped our radars for the clear-air turbulence project and were successful in detecting the presence of the tropopause eight times on five different days. The echoes detected were shown to be unquestionably from the clear air (by the wavelength dependence); they were almost coincidental with the tropopause layers as measured independently by radiosonde.

To detect the tropopause there were no major changes made on the radars. The radars had been built to detect small targets at ranges of several

hundred miles and they were used in the present application at ranges of 20 miles. Pattern recognition, slow scan, and film integration provided the additional improvement necessary to achieve tropopause detection.

The clear-air tropopause layers were found to be 200 to 250 meters in thickness and had reflection coefficients consistent with those expected from a refractively turbulent medium. Indications are strong that the layers are also mechanically turbulent.

Clear Air Echoes

For a 6-week period during May and June of 1966 an intensive program to investigate the structure of the lower atmosphere was conducted at the Wallops Island site with support of the extensive NASA facility together with specially equipped aircraft. Two airplanes and a helicopter were provided by the Air Force and the Navy. A photograph of the helicopter with the suspended refractometer package is shown in Fig. 5 about to take off for a flight. Equipment to measure the refractive index was supplied by British and Canadian teams. The aircraft were sent to probe regions of the clear atmosphere from which radar echoes were being received.

The success of the experiment was immediately obvious. Although we had expected to find evidence of angel activity we were quite pleased with their prevalence. We saw clear air echoes every

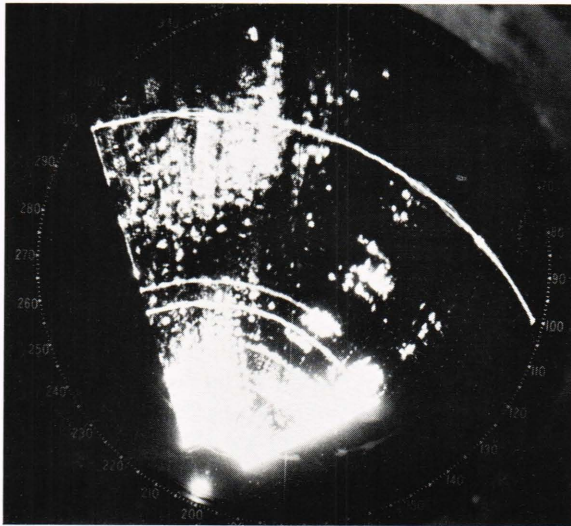


Fig. 6—PPI scope photograph on May 18, 1966. The outer range marker is at 20 miles. The separate white patterns are returns from clear air convective regions. The close-in bright areas are ground clutter.

day of operation. In the clear air we found convective cells forming and dissipating during the daytime over land. We also found considerable evidence of clear air layers forming at various elevations from near the surface to as high as 22,000 feet.

Cellular Structure

The clear-air cells tend to form during the morning, reach maximum development during mid-afternoon, and disappear for the most part around sunset. In the case of moist air flowing inland off the nearby ocean, the cells are fairly small close to the radar site and become larger and extend to higher altitudes as the air travels more and more over land. At times, the cells are aligned with the wind at the altitudes at which they are observed. On the plan position indicator (PPI) display the cells are more or less disc shaped. A sample PPI presentation showing convective cells is illustrated in Fig. 6. The corresponding range-height indicator (RHI) display (Fig. 7) shows a vertical cut through this structure. Notice the increase in size with range from the station. These cells are remarkably like the thermals which are used effectively in glider flights.

One of the most powerful aspects of the Wallops Island radar system is the availability of multiple radar frequencies for simultaneously illuminating a region. With the three frequencies we can determine which echoes are from clouds (water particles) and which are from index of refraction discontinuities. Generally, clouds are visible on the 3.2 cm and 10.7 cm radars while clear air echoes are detected on both the 10.7 and 71.5 cm radars. (This is discussed later in the article.) We can thus distinguish between clear air echoes and clouds even when a low overcast obscures our direct observation from the ground.

Layers

During the 6-week experiment described above, whenever we were observing, we saw at least some indication of layered structure. There was no obvious diurnal effect with layers as appeared with convective cells. The layers appeared to change somewhat with time and were not necessarily uniform in all azimuthal directions. A favorite region for formation of layers was at the elevation above the convectively mixed region, say about 5,000 to 7,000 feet. There were times, however, when we saw as many as a dozen distinctly different layers. Some of these layers were quite thin—of the order of tens of meters.

Aircraft Measurements

As stated earlier, we were in a position to measure the physical characteristics of the atmosphere rapidly and with precision with our airplanes or helicopter.

We dispatched one of the aircraft to probe in detail a selected layer or convective cell. Invariably, the refractometer operator would report a region of "disturbed" refractivity when entering the layer or cell. By disturbed we mean a region of unusual fluctuation in refractive index.

One mode of operation developed was the "linked mode" in which our 10.7 cm radar was put into automatic track with its tracking gate on the aircraft. Signal intensity measurements were made from a data range gate placed about 750 feet in front of the aircraft to avoid sampling air which might be modified by the aircraft itself. Aboard the aircraft simultaneous measurements were made of the refractive index of the air. On several aircraft traversals through convective cells like those in Fig. 7 a one-to-one correspondence was obtained between refractivity fluctuations and

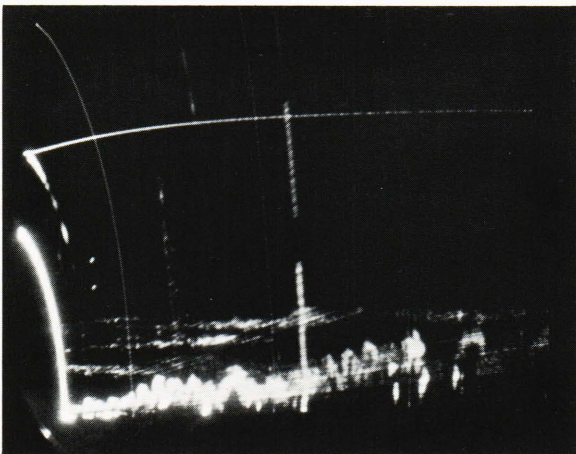


Fig. 7—The range-height display showing the same clear-air convective cells as in Fig. 6. The abscissa is range out to 20 miles, the ordinate is altitude with the nearly horizontal line the 20,000-foot marker. Note also some layered echoes above the convective regions.

the position of radar echoes. The results of one such flight are shown in Fig. 8. Signal strength is plotted versus time for an inbound run. In the upper portion of this illustration is an indication of the time during which the refractometer aboard the helicopter showed large variation in refractivity. When the 750-foot separation between the helicopter and the data gate is taken into account we find clear evidence of the relationship between high radar signal intensity and refractivity fluctua-

tions. Although we refer to these cells as convective cells, our measurements indicate that most of the refractivity change is caused by changes in moisture content rather than temperature.

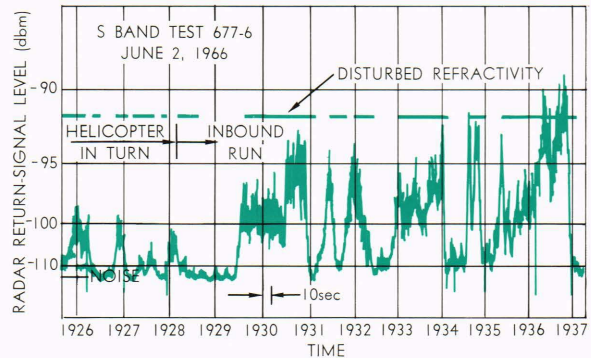


Fig. 8—Signal strength of clear-air radar echoes during a helicopter flight in which the refractive index was measured simultaneously. The times of large variance in refractivity are shown above the signal strength records. Note that during the inbound run there is a one-to-one correlation between high refractivity variance and high signal strength.

Theoretical Considerations

We were concerned with two types of scattering: (1) that from material particles like rain, insects, etc., and (2) that from inhomogeneities in the refractive index of the atmosphere. The wavelength dependence of these types are different and it is just this difference which we wished to exploit in distinguishing particulate from non-particulate (gaseous) scattering. We will note some of the highlights of the theory here.

PARTICULATE SCATTERING—The radar equation for a discrete target may be written:

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 r^4} \sigma, \quad (1)$$

where P_r and P_t are the power received and transmitted, respectively, G is the antenna gain, λ the wavelength, r the range, and σ the radar cross-section referred to previously. For a random distribution of targets we may write:

$$P_r = \frac{P_t A_e \tau \eta}{8\pi r^2}, \quad (2)$$

where $A_e = \lambda^2 G/4\pi$, τ is the pulse length, η is the cross-section per unit volume of the scattering particles. This is a simplified expression in which attenuation and gain differences across the beamwidth have been omitted. For small spherical particles like cloud and rain droplets the reflectivity per unit volume is given by:

$$\eta = \pi^5 \lambda^{-4} |K|^2 \Sigma D^6, \quad (3)$$

where D is the droplet diameter. The value of

$$|K| = \left| \frac{m^2 - 1}{m^2 + 2} \right|,$$

where m is the complex refractive index of the water particle. The region of droplet diameters for which Eq. (3) is valid is in the Rayleigh region and holds for $D \leq 0.06\lambda$. For water droplets whose diameters are larger, the ratio of the radar cross-section to the physical size is oscillatory with increasing diameter size and the exact value must be calculated by the exact Mie equations.⁴ For our purposes at Wallops Island it is the wavelength dependence in Eq. (3) which is of most interest. For the smaller clouds or rain droplets we look for a λ^{-4} dependence. For more details of this subject including the effects of droplet shape, spectrum of sizes, etc., the reader is referred to a paper by Atlas.⁵

NON-PARTICULATE SCATTERING—That a clear atmosphere will reflect electromagnetic waves was predicted by Friend⁶ as early as 1949. He assumed the existence of two layers in the atmosphere of differing refractive index separated by a sharp transition. He obtained a reflection coefficient

$$R = \frac{\Delta\epsilon}{4}, \quad (4)$$

where ϵ is the dielectric constant, which states simply that the voltage reflection coefficient is equal in value to one-fourth the dielectric transition difference for normal incidence.

More recently Tatarski⁷ and others have developed the theory for reflections from a refractively turbulent medium which may provide a better insight into our clear-air echoes. He gives the cross-section per unit volume of air

$$\eta = \left(\frac{\pi}{8} \right) (\overline{\Delta n})^2 k^2 F_n(k), \quad (5)$$

where $(\overline{\Delta n})^2$ is the mean square refractive index fluctuation, $k = (4\pi/\lambda)$ for the back-scatter direction, and $F_n(k)$ is the one-dimensional wave number spectrum of refractive index. This may be interpreted as saying the radar "sees" irregularities or eddies in the atmosphere of a scale one-half the radar wavelength. The one-dimensional spectrum is given by

$$F_n(k) = \frac{2}{3} k_o^{2/3} k^{-5/3} \quad (k_o \leq k \leq k_m), \quad (6)$$

where $k_o = 2\pi/L_o$, L_o is the outer scale of turbulence or the largest eddy size in the inertial subrange, and $k_m = 2\pi/\ell_m$, ℓ_m being the smallest eddy size. If we substitute Eq. (6) into Eq. (5) we find

$$\eta \propto (\overline{\Delta n})^2 L_o^{-2/3} \lambda^{-1/3}.$$

Here we have a wavelength dependence of $\lambda^{-1/3}$ quite markedly different from the λ^{-4} for Rayleigh scattering.

Conclusions and Future Programs

The multifrequency high-power radars in use at Wallops Island for the past year have yielded results which confirm that birds, insects, and irregularities in refractivity in clear air are all readily detectable on radar. These results open new possibilities for the study of the habits and characteristics of birds and insects. More important, perhaps, they provide new possibilities for the atmospheric physicist in the study of the mass and momentum interchange processes between the sea and the air and also for the microscale processes within the atmosphere.

During the coming fall and winter, we plan to continue the tropopause study by measuring the degree of turbulence with aircraft and with our doppler radars. This would constitute a concentrated effort toward our major goal of detecting clear air turbulence. If the detections of the tropopause are indeed associated with mechanical turbulence as is suggested by theory we could then proceed to study the subsequent occurrences of turbulence and attempt to find their causes.

Acknowledgments

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⁴ J. J. Stephens, "Radar Cross-section for Water and Ice Spheres," *J. Meteorology*, **18**, 348-359, 1961.

⁵ D. Atlas, "Advances in Radar Meteorology," *Advances in Geophysics*, **10**, 317-478, 1964.

⁶ A. W. Friend, "Theory and Practice of Tropospheric Sounding by Radar," *Proc. IRE*, **37**, 116-138, 1949.

⁷ V. I. Tatarski, "Wave Propagation in a Turbulent Medium," McGraw-Hill Book Co., Inc., New York, 1961.