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FURTHER REMARKS ON ATMOSPHERIC PROBING BY ULTRASENSITIVE RADAR

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ABSTRACT

This paper is supplementary to that of Hardy and Katz. It emphasizes the meteorological value of the various capabilities of ultrasensitive radar, highlights the points of agreement and disagreement, and focuses upon the directions of promising research. The theory of backscatter from a refractively turbulent region is said to be confirmed by the radar observations both with respect to magnitude and wavelength dependence. A reason for the apparent discrepancy between the results of some of the forward-scatter experiments and theory is suggested. Disagreement still exists with respect to the origin of clear air sea breeze echoes; the author does not agree with Hardy and Katz that they are due to insects. However, it is agreed that some unusually widespread echo displays on clear days are indeed due to insects. The meteorological value of ultrasensitive radars demonstrated by Hardy and Katz, here, and by others is so profound as to demand their use in remote atmospheric probing.

1. INTRODUCTION

These remarks are in comment upon the presentation of Drs. Hardy and Katz entitled "Probing the Atmosphere with High Power, High Resolution Radars." Their paper provides a fairly comprehensive review of the theoretical and experimental foundations for the use of ultrasensitive radars and for the interpretation of the observations in terms of meaningful atmospheric structures. I am in essential agreement with their presentation of the basic background material and have but a few reservations which I shall mention. Thus, my remarks will be directed primarily at: (1) focusing attention on the meteorological importance of the various observations of which ultrasensitive radars are capable, (2) covering some of the points omitted by Hardy and Katz, and (3) pointing toward the directions which future research should take.

2. SOME POINTS OF AGREEMENT AND DISAGREEMENT

2.1 Confirmation of Theory of Turbulent Scatter

One of the most significant aspects of the Hardy-Katz (hereafter referred to as H-K) paper is the confirmation, at least for backscatter, of the theory of turbulent scatter of Tatarsky and others. This is vital if the reflectivity is to be interpreted quantitatively in atmospheric terms. H-K and their colleagues have presented an abundance of data which validate their Eqs. (1) and (3). In particular, all the radar data is in close accord with the $\lambda^{-1/3}$ relationship, within experimental error, and thus justifies the use of the $k^{-5/3}$ law for the one-dimensional spectrum of refractivity perturbations. The restriction, of course, is to wavelengths between 10 and 70 cm and to corresponding turbulent scales between 5 and 35 cm. Indeed, I believe it is mainly because the radar observations are concerned with the small scale (large wave number) end of the turbulence spectrum that the classical $k^{-5/3}$ law of the inertial sub-range is applicable. It is of interest that Lawrence (1968) also reports the validity of the $k^{-5/3}$ law in this range and somewhat beyond (i.e., to scales of millimeters) in his review of line-of-sight optical propagation.

2.2 Apparent Conflict with Tropo-Scatter

A long-standing question concerns the reasons why tropospheric radio scatter data fail to show general agreement with the $k^{-5/3}$ spectrum. For example, Bolgiano's (1964) experiments at 3.2, 10.7, and 35.7 cm wavelengths show that a 3-D spectrum of $k^{-11/3}$ (or $k^{-5/3}$ for the 1-D spectrum) is applicable only to the median summer time conditions while $k^{-9/2}$ (or $k^{-5/2}$ in 1-D) represents the winter median. Two possible reasons are suggested: (1) Bolgiano's data correspond to filtered turbulence scales of 1.2 m, 3.9 m, and 13.2 m at the radio wavelengths of 3.2, 10.7, and 35.7 cm, respectively; these are considerably larger than those filtered by the radars of H-K. (2) The tropo data were taken along the Gt. Circle path where the signal contributions due to partial reflection from the mean vertical gradient of refractivity may readily mask those due to turbulence. Of course, no such contribution is possible in the H-K data except at vertical incidence. I am convinced that the latter is sufficient cause for the apparent discrepancy. The fact that $k^{-9/2}$ (3-D) is applicable in winter is in itself strongly suggestive. This means that the apparent turbulence spectrum decreases more sharply with k than expected, thus producing relatively stronger signals at the longer wavelengths. Of course, we would expect the reflections from a stratified gradient of refractivity (i.e., an inversion) to increase with wavelength, and we know that such inversions are more common in the lower levels in winter than in summer.

But even in summer, when the median Bolgiano data accords with that of H-K, we may get simultaneous layer scatter in tropo paths along the Gt. Circle and turbulent scatter from the refractivity perturbations which tend to be colocated at the height of sharpest mean refractivity gradient. This is well demonstrated by the radar data of H-K, Lane (1964, 1967)* and Saxton et al. (1964)* which show incoherent layered echoes always associated with a stratum of sharp refractivity change. Also Lane's direct refractivity probes confirm the co-existence of strong refractivity perturbations and strong mean gradient. Accordingly, one might well regard Bolgiano's median summer findings of $k^{-11/3}$ (3-D) as strong

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*See references in preceding article by Hardy & Katz confirmation of the findings of H-K. While there may be other scatter experiments which can be cited in contradiction to the $k^{-11/3}$ law, I believe that most of them can be questioned on grounds similar to those noted above. In any case, there are no data yet which refute the applicability of this law to radar wavelengths.

I might add that these remarks pertain as well to the tropo-scatter review by Cox* who points out that the observations can frequently be explained either by turbulent scatter or layer reflection. In the light of our discussion, this is not at all surprising.

2.3 Reflectivity vs. Refractivity

Even more important than the confirmation of the wavelength dependence reported by H-K, is the validation of the magnitude of the radar measured reflectivity predicted by Eqs. (1) and (3) of H-K by the direct measurements of the refractivity spectrum as reported by Kropfli et al. (1968) (shown in Fig.15 of the H-K paper). This and the similar confirmation by Lane (1967) leaves very little room for doubt. Together with the wavelength dependence, we therefore have a solid basis for interpreting reflectivity in terms of the magnitude of C_n^2. How to interpret C_n^2 in terms of $\overline{(\Delta n)^2}$ - the mean square refractivity perturbation, L_o - the outer scale, ε - the eddy dissipation rate, etc. is another question.

2.4 Refractivity Perturbations vs. Insects

There is one point in the H-K presentation which bothered me greatly and probably disturbed others as well. This is their contention that my 1.25 cm sea breeze echoes (Atlas, 1960) and their convective patterns (i.e., their Fig. 8) are due largely to insects and not to refractivity perturbations. Their argument is grounded solely on the fact that the required C_n^2 of 10^{-11} $cm^{-2/3}$ is too large to be meteorologically plausible. One might challenge this argument on the basis of Lane's 1965 direct measurements of $\overline{(\Delta n)^2}$ up to 22 x 10^{-12} at the base of a sharp inversion. Combined with a small outer scale L_o of the order of 1 m, this would produce the observed C_n^2. While such a small L_o seems implausible, it may be reasonable under a strong inversion where vertical motions are suppressed. Moreover, if a $\overline{(\Delta n)^2}$ of 22 x 10^{-12} has been measured, even larger values are probable. Thus, I would hesitate to exclude C_n^2 values as large as 10^{-11} $cm^{-2/3}$, although it is admittedly a rare event.

More importantly, in the case of sea breeze radar observations, the radar pulse volume was a mere 70 ft off the ground and located at the shoreline with observers stationed on a 144 ft tower and on the ground with the express purpose of watching for birds and insects with binoculars. No insects were reported, and only a few birds. Admitting the possible difficulty of seeing insects the size of flies in concentrations of 3 per 10^4 to 10^5 m^3 by eye, we must recall that our 1.25 cm radar beam was extremely narrow - 0.3^o to half power points - and the pulse volume at the range of 0.8 Km amounted only to about 700 m^3. Accordingly, even with extreme concentrations of 1 per 10^3 m^3, we should have observed discrete point echoes. In fact the echoes were diffuse, solid, and virtually continuous. I am therefore unable to accept the Hardy-Katz thesis that insects were even partly responsible for the sea breeze echoes.

On the other hand, astounding though it may appear from their Fig. 8, I believe that insects may indeed be responsible for such echoes. The fact is that Lhermitte (1966), Lhermitte and Dooley (1966), and Browning and Atlas (1966)

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*See Section 5 these Proceedings

obtained Doppler velocity records over extended periods and at heights up to 2 Km under clear sky conditions and with 3.2 and 5.5 cm radars of modest power. Typical records of Doppler velocity versus azimuth are shown in the original papers. They show that the echoes are discrete in velocity and/or azimuth and unlike the truly continuous corresponding records obtained in precipitation. Thus, the scatterers are indeed point targets, and though the Velocity-Azimuth Display (VAD) shows them to move with the wind, they are most probably insects. Indeed the average reflectivity measured by Lhermitte and Dooley for their Oklahoma data at 3.2 cm was 3×10^{-12} cm^{-1}, identical to that of Hardy and Katz for the Massachusetts case. Moreover, they estimate a target concentration of 1 in 10^4 m^3, close to the concentration estimated by H-K. Independent Doppler observations by Browning and Atlas (1966) (also in Massachusetts) showed concentrations about 0.1 as large. Finally, since the Doppler targets were present for periods of 60 hours in Oklahoma and at least 7 hours in Massachusetts, and all the time moving with the wind, they must have been at least as spread in horizontal extent as shown in H-K's Fig. 8. Thus, we can be reasonably confident that those echoes are in fact due to insects.

This, at least, is my judgement. On the other hand, I think it equally likely that the 1.25 cm sea breeze data are due to refractivity perturbations and not insects. This implies that $C_n^2 = 10^{-11}$ $cm^{-2/3}$ is probably valid under some sea breeze conditions.

I have spent some time on the insect versus refractivity question because it is central to the issue of deducing the true atmospheric structure from the radar observations. Clearly, since both may occur either separately or at one and the same time, means must be provided to distinguish one from the other. This means has been clearly denoted by Hardy and Katz and by Hardy, Atlas, and Glover (1966); namely, the use of two or more wavelengths simultaneously. Indeed, had two wavelengths been available during the observations discussed above, the question could have been readily resolved. Of course, two wavelengths are also required to distinguish cloud and precipitation echoes from those due to refractivity perturbations. This is especially important in understanding the interactions between clear air circulations and precipitation; a subject which was not treated by Hardy and Katz. With sensitive radars one may detect the clear air convection which is responsible for the subsequent development of clouds and precipitation. One may also detect cloud boundaries by virtue of their refractivity perturbations and the cloud cores by means of the scatter from developing precipitation. Obviously the two must be distinguished if any sense is to be made of the observations.

In short, ultrasensitive radars do indeed provide a heretofore unimagined potential for probing the structure of the atmosphere. At the same time, they have shown how very complex the atmosphere is. Unravelling its secrets will be a formidable task. But recognition of the atmosphere's complexity and of the magnitude of the effort required to explain its workings is a notable sign of progress.

3.0 SOME OMISSIONS

By and large Hardy and Katz have concentrated upon the clear air phenomena which are rendered detectable by powerful radars. I would therefore like to say a few words about other important phenomena which may be studied by such techniques.

3.1 Clouds and Precipitation

I have already alluded to clouds and precipitation in another context; now I should like to stress the value of sensitivity and resolution in detecting young and tenuous clouds. Few people will deny that our present day knowledge of precipitation processes and storm structure stems largely from radar observations. This is especially true in the case of convective storms whose internal structure is not readily observed by any other means. But our understanding of the earliest stages of convective precipitation has remained rudimentary because the particulates are not detectable by radars of ordinary sensitivity. The use of sensitive radars will extend our "sight" to these crucial early phases - both in terms of the sub-cloud circulations and the pre-precipitation cloud structure made visible by refractive index anomalies, and in terms of the smallest precipitation elements. At the same time, the increased resolution will permit us to dissect the small young clouds about as well as our broad beam "scalpels" now permit in the case of the larger storms. But increased resolution is equally important in the latter as well because existing beams present a highly degraded image of storm structure. I needn't belabor the point because the resulting distortions are obvious.

Increasing radar sensitivity by two to three orders of magnitude (i.e., the sensitivity ratio of the Wallops to "typical" existing meteorological radars) also extends our observational realm to a vast hierarchy of previously undetectable tenuous clouds. For example, the cirrus clouds shown so well in Fig. 1 of Hardy and Katz were rarely seen before by radar, and then only by fixed vertically pointing short wavelength systems. These and others are important both in their own right and by virtue of providing tracers of atmospheric motion. Their use opens up all sorts of interesting possibilities for studying turbulence, wave motions, and meso- and large-scale atmospheric circulations. The fact that we can now see clouds in the high troposphere and low stratosphere also suggests that we may be able to examine the dynamic links from one to the other. In short, dramatic though they are, the Wallops observations have only hinted at what greater radar sensitivity and resolution holds in store for the atmospheric sciences.

3.2 Turbulence Measurements

Hardy and Katz have suggested that the reflectivity of clear air echoes is related to ε, the eddy dissipation rate of turbulent energy (their Eq. 5). While there is indeed some relationship, I believe that it will be obscured by the dependence upon the refractivity gradient. However, the point is not worth argument because we have the means of measuring turbulence directly.

The intensity of turbulence may be obtained directly from

$$\Sigma_v^2 = \sigma_{<v>}^2 + \overline{\sigma_v^2} \qquad (1)$$

after Rogers and Tripp (1964). Here $\overline{\sigma_v^2}$ is the mean variance of the Doppler spectrum of the echoes and corresponds to scales of turbulence smaller than the pulse volume; $\sigma_{<v>}^2$ is the variance of the instantaneous mean Doppler velocity and corresponds to scales of turbulence larger than the pulse volume. Of course, the total turbulent energy is the sum of the two. While there are practical problems in deducing σ_v^2 from the total variance of the Doppler spectrum (because factors other than turbulence contribute to it - Atlas, 1964), these are minimized in clouds of small particulates and snow. In addition to the direct measurement of turbulence intensity one may analyze the temporal or spatial variations of mean Doppler velocity to obtain the spectrum of large scale turbulence. Gorelik (1965) in the Soviet Union and Rogers and Tripp (1964) have exploited these ideas to provide previously unobtainable data on the characteristics of turbulence in the free atmosphere. (See the review by Lhermitte in these Proceedings for further details.)

Of course the techniques of radar turbulence measurement are not restricted to ultra-sensitive radars. However, the ability of such radars to detect both clear air echoes and tenuous clouds, especially in the high troposphere, greatly extends their turbulence probing utility. It seems clear that future studies of clear air turbulence should take advantage of this important capacity.

3.3 Wind Measurement

Lhermitte's review speaks extensively of the use of Doppler radar for wind measurement. It bears repeating here because ultra-sensitive radars can detect wind-borne scatterers - either cloud and precipitation elements or clear air turbulent eddies - through most of the troposphere and during a great part of the year. I venture to predict that a modest increase in sensitivity over that of the Wallops 10 cm radar will make it possible to detect wind-borne scatterers throughout the troposphere throughout the year, at least at short ranges. Thus, I suggest that we should be able to measure tropospheric winds effectively instantaneously and continuously. Such an observing capability would have a tremendous impact on our understanding of atmospheric circulations on all scales.

3.4 Lightning and Sferics

Very little work has been done in the way of radar lightning detection since the 1950's when Ligda (1956), Hewitt (1957), and Atlas (1958) showed that radars between 10 and 50 cm wavelength could detect and map lightning produced ionized paths and the radio noise (sferics) radiated therefrom. The new generation of radars have a great deal to offer in this regard. The greater sensitivity will permit the detection of much smaller electron densities and thus provide a means of studying both the earlier stages of electrification and the later phases of lightning decay. The use of two or more wavelengths will permit better discrimination between precipitation and lightning and show where in the storm electrification is initiated. Such observations should suggest how the precipitation mechanism controls or influences lightning, or as proposed by Moore, et al., (1962), whether lightning triggers precipitation. We need also to learn how the lightning propagates within the storm cells, from one cell to another, from cloud to ground, and from cloud to ionosphere. Such data should be attainable by the clever use of several beams at two or more wavelengths.

The use of the radars as high resolution sferics receivers should also be most enlightening. First of all it should permit us to isolate the electrically active regions of clouds and storms in relation to their precipitation structure as seen by active radar. Surprisingly, we have only the crudest knowledge of this relationship. In addition, the combination of great sensitivity and high resolution will permit a search for and confirmation of the existence of the weak electrical discharges which are associated with particle coalescence and which may occur in clouds which never reach the thunderstorm stage (Sartor, 1964; see "Sferics" review by Pierce in these Proceedings). Finally, much can be learned of the fine scale structure of the discharges by studying both the time-variation of the radiated signals and their dependence upon wavelength (see Pierce).

In short, it seems clear that we have much to learn about cloud and storm electrification; and the use of ultra-sensitive radars at two or more wavelengths offers us many interesting opportunities in this regard.

3.5 The "Pictorial" Value of Radar: A Lesson to be Learned

At the risk of stating the obvious, I consider it important to stress the value of the "pictorial" or mapping capacity of radar. Although the structure of precipitation echoes can be exceedingly complex, sense can be made of them because they are depicted in two or three dimensions and can be related readily to familiar structures which we have seen by eye. In short, the significance of a set of point observations in space or time remains obscure until they are pieced together as a unified entity. Satellite cloud photography is a dramatic example of the synergistic value of the whole cloud field in relation to that of the set of individual pieces of the puzzle.

This should teach us an important lesson in all approaches toward remote probing; namely, to map the observations in some familiar spatial coordinate system. In the case of radar, Hardy and Katz put it succinctly when they state: "Methods must be devised to measure, analyze, digest, and put into useable form the 3-dimensional picture of the wind field." Indeed, I feel quite strongly that much of the seeming complexity and ambiguity which has characterized tropospheric radio scatter measurements would be removed if we were to display the observations in time and/or space coordinates. Cox implicitely recognizes this problem in his review of tropo-scatter (in these Proceedings) when he states that the data are characterized by great variability and so reflect the variability and complexity of the atmosphere. Similarly, the suggestion by Hardy and Katz to utilize radar observations simultaneous with forward-scatter measurements emphasizes the need to combine various observational tools to provide greater significance than can be obtained from either alone.

4.0 CONCLUDING REMARKS

The reviews by Hardy and Katz and by Lhermitte, along with the supplementary remarks presented above, provide impressive evidence of the worth of ultra-sensitive multi-wavelength radars to the atmospheric sciences. But they provide only a hint of things to come.

We are now at a stage analogous to that of the early astronomers; the history of their progress has been linked to the power of their telescopes. The same is true in radio and radar astronomy, in electron microscopy, and in virtually every experimentally-based discipline. Thus, it is no longer a question as to whether or not to proceed to radars of greatly increased sensitivity and resolution, but how to proceed.

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