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# AIRBORNE DOPPLER RADAR FOR WIND SHEAR DETECTION

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## INTRODUCTION

There has been extensive discussion concerning the use of ground-based Doppler radars for the detection and measurement of microburst features and the mapping of associated wind shears. In this paper, I shall address recent and planned research at the Langley Research Center into technology and techniques useful for the future development of airborne Doppler weather radar systems for both turbulence and wind shear detection. Such systems, if successfully developed, would represent a marked increase in performance over airborne weather radars currently available. A principal difficulty in extending to airborne radars the capabilities of current ground-based Doppler radars can be seen in the following way.

Consider an airborne radar observing a resolution cell ahead of the aircraft. The transverse dimensions of the cell are determined by the width of the antenna main lobe and the longitudinal dimension by "range gating" the received signal. Within this cell, a population of water droplets scatters power back to the radar, and the magnitude of this power is related to the rainfall rate or "dBZ" level of the cell. Until recently this power level was the only measurement available to airborne weather radars. Additionally, the frequency of the radiation scattered by each droplet is altered from that of the transmitted signal by the relative radial velocity between the droplet and the radar. A Doppler radar is sensitive to these frequency shifts and is, thus, able to measure radial velocity features of the cell. The horizontal velocities of the droplets tend to equilibrate with the local wind field, so that the Doppler spectrum of the received radar signal is a measure of the radial component of the horizontal turbulence spectrum, appropriately averaged over the cell. The mean value of this spectrum is then related to the mean wind velocity in the cell. If this mean velocity is measured cell-to-cell, then the large-scale wind variation, or wind shear, can be measured along with the turbulence within each cell.

Because of the rapid motion of the aircraft, the absolute values of these mean radial relative velocities are much larger than those usually encountered with ground-based radars. Further, the resulting measured velocities vary widely with antenna scan angle. These factors combine to make very difficult the measurement of mean wind velocity with an airborne radar. In fact, the newest generation of commercially available airborne Doppler radars makes no attempt to do so. In the next section I will describe some past experiments by the Langley Research Center with a radar developed in-house for the purpose of making both turbulence and mean velocity measurements.

## PAST EXPERIMENT PROGRAM

In the summer of 1982, experiments were performed involving two aircraft and a ground-based Doppler radar in the environments of the NASA Wallops Flight Center. One of the aircraft was the Langley F-106 thunderstorm penetrator, which is involved in the aviation Storm Hazards Program under the leadership of Norman Crabill. The F-106 contained instrumentation for measuring the complete turbulent wind field and resulting aircraft accelerations within a thunderstorm. The second aircraft was the NASA Wallops "Skyvan" in which was installed the Langley airborne pulsed-Doppler research radar system. The objective of the Skyvan was to position itself outside of a thunderstorm such that its on-board radar could observe the storm environment in which the F-106 was simultaneously flying. The ground-based Wallops "Spandar" radar was provided with separate sets of equipment by both Langley and the Air Force Geophysics Laboratory for the collection of Doppler radar "truth" data. Figure 1 is a sketch of the experimental configuration.

As can be seen, the two aircraft would position themselves such that both would fly along a radial line to the Spandar radar. The Skyvan radar would view rearward along its line-of-flight while the F-106 would make passes in both radial directions through the thunderstorm. Data were collected for several thunderstorms on a smaller number of thunderstorm days. In order to measure successfully the mean wind velocities along the line-of-flight, the Skyvan research radar utilized a special airspeed compensation scheme. This compensation involved a computer-aided feedback loop which was used to track the relative velocity between the Skyvan and a resolution cell under observation and to control an oscillator in the radar so as to translate the Doppler spectrum into the first "Nyquist interval". In this way, all of the Doppler information, including both mean and turbulent velocities relative to the Skyvan, could be recorded unambiguously. It should be emphasized that this scheme required no real-time input of air or ground speed to the radar.

Figure 2 shows a sample of data collected by the Skyvan radar. Plotted is mean radial velocity versus distance from the Skyvan. Shown in the lower right corner are mean velocity values for successive range bins for two adjacent pointing directions. The curves show gradients in the mean wind, i.e., shear, both along the transverse to the line-of-sight of the radar. The measured values of the shear are typical of those known to occur in representative thunderstorms. What is important here is that these curves illustrate that radar techniques of the kind used can, in fact, measure wind shear aloft despite the rapid aircraft motion. Measurement of hazardous wind shear near the ground, however, is a much more difficult matter and will require even more sophisticated radar techniques. The next section will offer some considerations relative to the detection of microbursts at very low altitudes with airborne radar.

## LOW-ALTITUDE WIND SHEAR DETECTION

Several new aspects appear for the airborne weather radar when applied to operations near the ground. Some of these pertain to:

- Vertical resolution and its effects on microburst "signature" recognition and shear-induced spectral width;

- Ground clutter contamination in both main and side lobes.

Consider an aircraft on its final approach at a distance of 10 km from touchdown and descending along a 3° glide slope. Its altitude at that point is about 500 meters. Since the antenna beamwidth of a currently typical airborne radar is also about 3°, the vertical extent of the radar resolution cell at the point of touchdown is also 500 meters. Now the predominant outflow

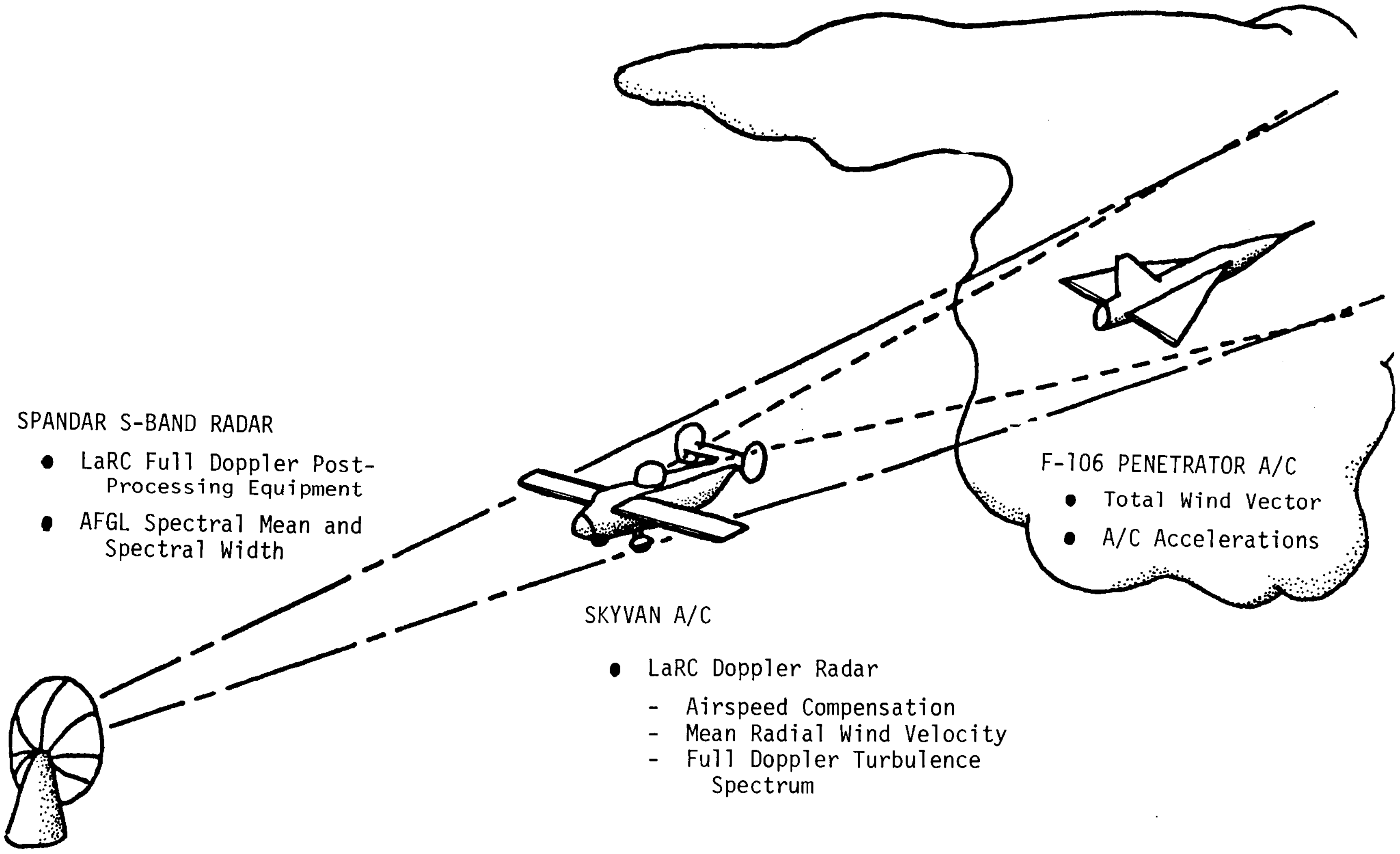

Figure 1. Doppler Radar Turbulence - Wind Shear Experiments (Summer 1982).

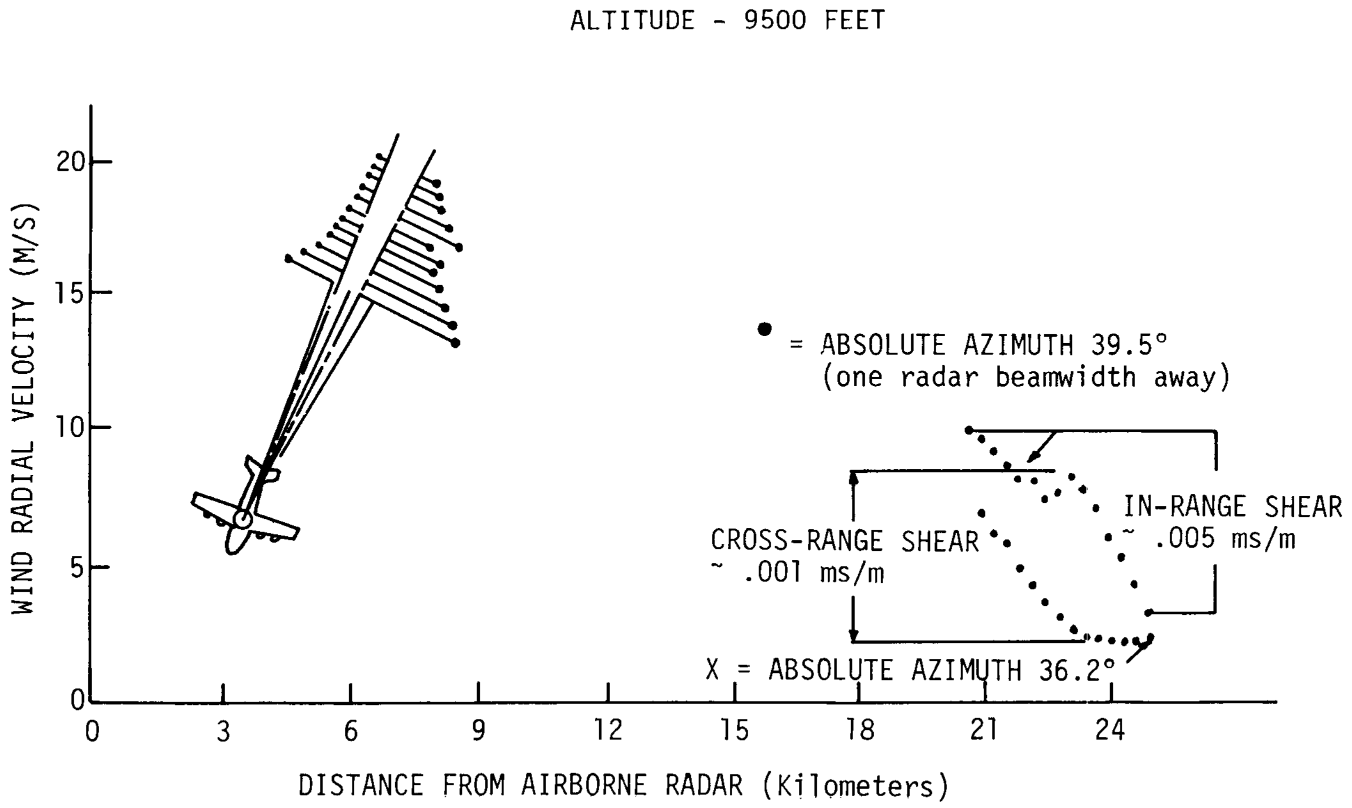

Figure 2. Wind radial velocities measured with airborne radar in thunderstorm of July 28, 1982.

from a microburst occurs below 1 km, so that two vertically contiguous resolution cells would cover the outflow region. To do this effectively, however, the radar antenna would need automatic scanning in the vertical direction. Present airborne weather radars do not have this feature, but a more serious problem with this vertical resolution cell size is the velocity spectral width that must be dealt with.

It seems that in the passage of a typical thunderstorm, there is a 50/50 chance that the vertical shear in the horizontal wind passing the tower will exceed 25 meters/second over the height of the tower (500 m). Even in the absence of any actual turbulence, this amount of shear would produce an effective turbulent spectral width that is wider than that which can be handled by the latest commercial X-band airborne Doppler radars. This spectral width coupled with the large horizontal gradients in the microburst outflow would require dramatic increases in the transmitted pulse repetition frequency (PRF) of a conventional pulsed-Doppler radar. Increasing the PRF can, in turn, cause problems with "second-time echoes", which are signal returns that lie beyond the ranging capability of the radar and appear to the system to lie much closer than their true positions.

Perhaps one of the more serious potential problems facing the airborne wind-shear radar is the contamination produced by spurious returns from portions of the ground contained in the antenna side lobes. The relative velocity of these signal returns ranges from zero for signals received abeam the aircraft up to the ground speed for signals directly ahead. If these side lobe clutter signals are sufficiently strong, then no practical value for the PRF could be achieved, and more complex modulation schemes would be needed. It is, of course, not clear to what extent the above conclusion from tower data is representative of microburst conditions or how difficult the side lobe clutter will really prove to be. However, if analysis of JAWS and similar data supports the need to deal with such shear levels, then substantial changes in airborne radar characteristics may be required. Since a recent joint study by a committee representing the National Research Council [1] has advocated research into the use of airborne Doppler radars for ameliorating the wind shear problem, there is renewed interest in structuring an appropriate research program to define actual conditions and to support development of those new radars.

## PROPOSED AIRBORNE RADAR RESEARCH PROGRAM

In order to answer some of these questions, a new research program has been proposed by the Langley Research Center for joint support by NASA and the FAA. The program has among its goals the following items related to the physics of the measurement and the interpretation of the associated hazard:

- Extraction of the raindrop "clutter-like" signal from the (moving) ground clutter;

- Scanning techniques for measurement of the microburst "signature";

- Determination of the utility of frequencies above X-band;

- Development of hazard recognition and alarm algorithms from the measured signatures;

- Development of practical methods of obtaining high-quality field data with reasonable aircraft flight time.

A first job is to determine what existing instrumentation can be of value to the new program. The present status of airborne Doppler weather radars can be represented by the characteristics of three radar systems. These are a) the NOAA-P3 X-band airborne radar and its improved version presently being developed by NCAR; b) the NASA Langley airborne Doppler research radar; and c) the newest commercially available airborne turbulence radars, a representative of which is the Collins WXR-700 model.

The NOAA-NCAR Doppler radar has been successfully used in a variety of atmospheric research programs. Its chief limitation for purposes of developing the desired new wind shear radars is that its antenna is mounted in a tail-sting radome and is constrained to view perpendicularly to the line-of-flight. Accordingly, it has no need, and no capacity, for elaborate airspeed compensation functions. It does have a relatively narrow antenna beamwidth, but this is obtained from an antenna that is too large for general application in the nose radomes of most aircraft.

The NASA Langley radar has been discussed earlier. Its salient characteristics are as follows:

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|---|---|
| - Frequency: | 13.9 GHz |
| - Pulse rep. freq.: | 3000/sec |
| - Pulse length: | 2 microsec |
| - Antenna beamwidth: | 3.3 deg |
| - Trans. power: | 2 kW peak |
| - Unambiguous range: | 50 km |
| - Unambiguous velocity: | ± 16.2 m/s about compensated airspeed |
| - Res. cell length: | 300 m |

Major limitations of the radar for the low-level wind shear research application relate to its inflexible pulse modulation parameters and antenna characteristics.

Representative of the new commercial airborne radars is the Collins WXR-700, which has the following characteristics:

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|---|---|
| - Frequency: | X-band |
| - Pulse rep. freq.: | 1440/sec |
| - Pulse length: | 6 microsec |
| - Antenna beamwidth: | 3.2 deg |
| - Trans. power: | 125 W peak |
| - Unambiguous range: | 104 km |
| - Unambiguous velocity | ± 11.4 m/s (spectral width only) |
| - Res. cell length: | 900 m |

The large resolution cell size (approximately 1/3 of a runway length) and the rather small unambiguous velocity interval of such a radar may be inadequate for the needed research program, although a modified version of it could well be useful in the upward-looking mode while stationary on the ground. It is evident from the above that a new airborne radar research instrument is required for the new program.

The proposed radar system will be modularly constructed such that different transmitters and modulating schemes may be used with common intermediate frequency and "back-end" electronics. It is planned to have dual receiver channels so that both direct and cross-polarized signals can be studied; thus, dual receiving antenna positions can be used. To overcome the difficulty of gathering a sufficient quantity of airborne data to study both microburst and ground-clutter features, it is proposed that data be collected in two separate forms and merged later.

First, a suitable ground-based radar would be configured such that it truly represented airborne radar characteristics. This radar would be deployed as part of a joint field program for the study of airport weather such as that currently being conducted by the FAA in Memphis, Tennessee. In this mode, the radar would obtain full time-series data on weather targets of opportunity in the presence of "truth" data provided by other sensors. This radar data would have the effects of (non-moving) ground clutter removed by conventional means. Later, the completed airborne research radar would fly airport passes in wet weather but not necessarily in microburst conditions. The primary purpose of these flights would be to obtain full time-series data for the moving ground clutter. After suitable adjustment of the "noise-levels" of the two sets of data, airborne and ground, the time series would be combined to represent a composite signal having both microburst data and realistic airborne ground clutter. Upon this "truth data" candidate algorithms and techniques for true wind shear signature extraction could be verified. Promising approaches could then be implemented in hardware for future flight testing. The research program described would, thus, significantly involve analytical and computer studies as well as radar hardware. To carry out such a program, it is evident that expeditious use must be made of all data presently available, such as that obtained in JAWS.

## WIND-FIELD AND RAINFALL MODELS FROM JAWS

Should the program discussed receive appropriate funding in the fall of 1984, it is proposed immediately to begin cooperative efforts with interested JAWS investigators. A workshop will be held at Langley involving them along with representatives of the weather radar community to help fashion the wind shear program in the most effective way. Interaction with JAWS researchers would seek to define wind-field models to denote what a single, moving radar might see in approaching an airport. These wind-fields, along with realistic rainfall rate models, would serve as the initial basis for developing expected radar signatures in the early analytical work. Techniques developed in this early work could then be tested against a larger body of data as the JAWS data reduction continued. Although the final test of the wind shear radar must come in the air, data such as that from JAWS will be of inestimable worth in designing it and proving its technology.

## REFERENCE

1. NRC-NAS Committee on Low-Altitude Wind Shear and its Hazard to Aviation: "Low-Altitude Wind Shear and Its Hazard to Aviation;" National Academy Press, Washington, DC, 1983.

## QUESTION:

Previously, there was some discussion about airborne radars being ineffective when no moisture is present in the air. However, it was also stated that even though no moisture is present, there are generally a lot of bugs, and you can measure the velocity of the insects. Apparently this was based on experience in the JAWS data experiment. Could you comment on whether this has been your experience?

## RESPONSE:

Insects of all kinds have been seen on ground-based radars for years. It is now thought that they account for a large number of the angels or false echoes that were seen and were regarded as completely unexplainable. On our airborne radar I have never seen anything which I would associate with an insect; but I haven't looked for it, either. I would think, however, that the insect population would be sufficiently sparse to have very many of them in a resolution cell. If you have two of them, for example, those signals beat together and result in a highly fluctuating target with only two samples in it. To get a good stable target there needs to be a large number of drops (certainly over 10, and maybe even 100) in a resolution cell. Even though you may see them, they are not complete tracers of what is going on in that cell; certainly not in the tracer of the turbulence.

## QUESTION:

The work done in Severe Storms Lab and at Boulder seems to contradict that. There are two sources of reflectivity on ground-based radars which are showing up very heavily in the optically clear air. These are refractive index gradients and insects. Some work done particularly at the Severe Storms Lab shows that the insect population in convective boundary layer is extremely high. They represent a substantial reflectivity source. Combined with refracted index gradients, a very sensitive ground-based radar, obviously with a large antenna, is quite capable of seeing all kinds of action in the convective boundary layer. I think the issue here is whether an airborne system can be designed with sufficient sensitivity to get targets in the optically clear air. That, to me, is the nature of the question. There is no doubt that there is a lot of reflectivity in a summer-type convective boundary layer. Every ground-based Doppler radar is seeing optically clear air, and getting good velocity measurements in it.

## RESPONSE:

Yes, I have done some work in looking at the optically clear air with a 60 ft. dish antenna at Wallops. At S-Band, you have to work at it a little in order to see things at very high altitude; therefore, it is not the kind of thing that reasonable airborne radar will be able to do.

QUESTION:

Again, this only works on a ground-based radar in the boundary layer where there are bugs and, also, refracted index gradients. Above the boundary layer, it is zero. There is nothing there; but with the microburst signature, we're talking about convective boundary layer.

RESPONSE:

That is an interesting point which certainly deserves to be looked at.

QUESTION:

Do you see a reasonable antenna size in the future, say after 1987?

RESPONSE:

Yes, if you're talking about larger airplanes. I think we can talk about 3 ft. or so, reasonably, for something that might be put in the radome as an upper bound. If we want to look at smaller airplanes, of course, that commercial sizes. Twenty-four inches at X-Band gives you about 3°; thirty inches would be a little less than that.

QUESTION:

Would you discuss the use of airborne Doppler radar for the cruise mode of flight? You would size it so that it would take care of the wind shear environment at low altitude. How about the cruise conditions at a higher altitude in terms of still being able to get the reflectivity turbulence and winds?

RESPONSE:

I mentioned the possibility of the ultimate radar being a higher frequency; in fact, we want to do some experiments up to 35 GHz. Since we are lower to the ground and don't have to see as far, we could probably get away with lower power levels at that higher frequency than we would for the en route problem. So, it could well be that the final radar would be a dual-frequency radar where everything from the IF on down would be common to both of them; but we would switch between two transmitters. There are any number of things that might accommodate that. Certainly, to make it useful and acciptable, these functions must be included in the weather radar. I would like to add that general purpose radar (which we are talking about building) obviously has more performance potential than we're ever going to have in any real radar that's useful. That we have to do is abstract from all these variables the things which we really can use to identify the signature, and use only those in the operational version.

QUESTION:

I realize that this is limiting, but if we are specifically interested in detecting microbursts when we are at low altitude, rather than looking, necessarily, at an elaborate horizontal signature in front of the aircraft, the really strong identifying feature is the vertical shaft. It is conceivable that this radar, instead of looking in front of the airplane, should be looking upward, for example, at 45° when it's in the landing mode. This would solve the ground clutter problem and also be specifically designed to look for that vertical shaft. That, in combination with the fact that you have suddenly nosed up because of a sudden head wind, would be sort of a dual confirmation that there is a microburst.

RESPONSE:

By the time you have nosed up, you are already in a regime where your radar has not done you much good. The advantage of radar is to be able to see ahead of the airplane. Now, whether we could identify this feature looking up at 45° would have to be answered by something like the JAWS data. If that feature shows up, then by all means, we would include that vertical scan.