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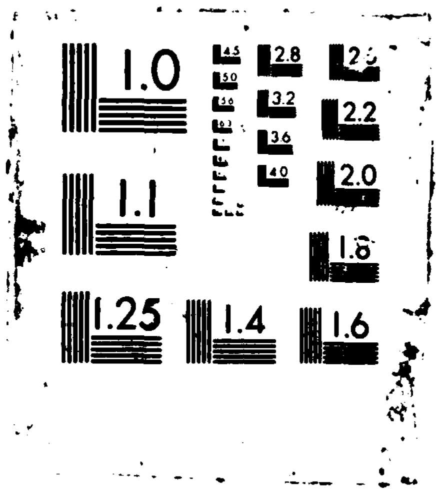
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The project was concerned initially with the development of a Doppler radar operating a 94 GHz (3 mm wavelength) primarily for the study of dynamical processes in clouds in the early stages of their development. The observation of other weak targets such as particulates suspended in the earth's atmosphere was also included in the research as

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MILLIMETER WAVE DOPPLER RADAR OBSERVATION OF CLOUD AND BOUNDARY LAYER STRUCTURE

FINAL REPORT

BY

ROGER M. LHERMITTE

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UNIVERSITY OF MIAMI
ROSENSTIEL SCHOOL OF MARINE & ATMOSPHERIC SCIENCE
DIVISION OF METEOROLOGY & PHYSICAL OCEANOGRAPHY
UNIVERSITY OF MIAMI
4600 RICKENBACKER CAUSEWAY
MIAMI, FLORIDA 33149-1098

1. Foreword

Although microwave radars are very useful for monitoring storms and precipitation, they are not capable of observing clouds unless they are equipped with a large antenna and a powerful transmitter to overcome the weakness of cloud droplet backscattering at centimeter wavelengths. Furthermore, even if the microwave radar sensitivity is sufficient so that a signal above the receiver noise is obtained even for weak backscattering, the radar detection of these weak targets may be hampered by the presence of strong ground clutter "seen" through the antenna sidelobes.

As backscattering signal intensity increases with $1/\lambda^4$ (Rayleigh scattering small targets), the use of a radar operating at a very short wavelength (millimeter wave) provides a substantial enhancement of weak targets' radar reflectivity. Comparing an S-band radar to the millimeter wave ($\lambda = 3$ mm) radar we have developed, shows an almost 60 dB enhancement of small cloud reflectivity. The ground clutter echo intensity does not vary much with wavelength (in fact it decreases slightly). Therefore, the cloud/ground clutter contrast is expected to increase by at least 60 dB switching from an S-band to a W-band ($\lambda = 3$ mm) radar operation. The size and weight of the radar will also be considerably reduced thereby improving portability. The improvement of Rayleigh gain with respect to X-band ($\lambda = 3$ cm) is still 40 dB and the antenna diameter required for a 0.5° beamwidth is approximately 14 feet at X-band and less than 2 feet at W-band.

These considerations and the onset of a research program devoted to the study of dynamics of small clouds appeared earlier as strong incentives for the development of a millimeter wave Doppler radar designed for the observation of small clouds and other small meteorological targets. The radar was developed earlier and was tested in the beginning of this contract. This testing period was followed by the development of a Doppler signal processor and several atttempts to use the radar for observation of meteorological targets such as small cumulus and cirrus clouds. The continuity of these observations was hampered by the constant failure of the 94 GHz transmitter. The transmitter/modulator unit which was purchased from Varian Associates produces a pulse with low phase noise and fast rise and fall time indicative of an excellent design; however, it failed repeatably and had to be repaired several times. It is now working satisfactorily and the cloud observation schedule has been resumed.

In the first period of the contract the millimeter wave Doppler radar testing was completed and observations were made at the Miami site. The equipment was later moved to Boulder, CO, where cloud and precipitation observations were made in cooperation with the National Center for Atmospheric Research.

Five papers discussing the Doppler radar and the research program and results were published in 1985-1986 (see bibliography and the attached reprint volume titled: "94 GHz Doppler radar project"). Results of this research was presented at several meetings: NCAR Airborne Doppler Symposium, Boulder, CO [4]; URSI Open Symposium, Durham, NH [5]; Remote Sensing Conference, Hamburg, West Germany [6]; Cloud Physics and Radar Conference, Snowmass Village, CO [7]. This final report summarizes the work accomplished and the state of the research. A more detailed description of the research achievements can be found in these attached papers.

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4.a. Statement of problem studied.

The primary application of the 94 GHz Doppler radar was to study the dynamics of small cumulus clouds in the initial stage of their development. The conditions of radar reflectivity development indicative of particle growth and the observation of updraft (and also downdraft from continuity) produced by the latent heat release associated with that growth, can be effectively monitored by the millimeter wave Doppler radar.

This may be done best using the millimeter wave radar aboard an airplane flying above the clouds and essentially probing radar reflectivity and vertical velocity in a chosen vertical plane hopefully going through the cloud center. However, observations of this type can also be conducted using a ground based radar with a vertically pointing beam. The success of such observations relies on the probability that a cloud drifting over the radar site intersects the radar beam. In the case of random develoment of fair weather cumuli observed with the radar for several days, the probability of catching a few representative samples is good enough to justify the method. The visible image of the cloud should also be monitored by a video camera system attached to the radar to facilitate the interpretation of the results.

We therefore proposed to develop the techniques and methods for such a research program and to conduct the experiments. In addition to this research program, we also proposed to study the velocity field inside a cloud of heavy particulate in the boundary layer in an effort to study boundary layer turbulence. More recently the project was extended to the study of backscattering of 94 GHz radiation due to ground snow cover.

4.b.1. Doppler radar and signal processing.

The millimeter wave Doppler radar was developed earlier and is described in [1],[2], and [3]. It operates at a frequency of 93.45 GHz and has the following main characteristics.

1). Peak power 1 kw
2). Receiver sensitivity -93 dBm (-115 dBm with 3 s signal integration).
3). Antenna beamwidth 0.27°
4). Pulse repetition rate adjustable from 2.5 kHz to 20 kHz
5). Pulse width adjustable from 0.1 μs to 2 μs

Based on these radar characteristics and a 400 ns pulse width, the target (cloud) radar reflectivity in dBZ is expressed by [3]:

$$dBZ = P_r\ (dBm) + 53 + 20 \log R$$

The receiver noise is -93 dBm but, with the processor integration gain, an echo -20 to -25 dB below the noise can be detected and the Doppler velocity effectively measured. Maximum two-way atmospheric absorption in a vertically pointing mode is 3 to 8 dB (primarily concentrated at low altitude levels) depending on humidity conditions.

Therefore, a target with radar reflectivity greater than -45 dBZ can be effectively observed at a 3 km vertical distance. A fair weather cumulus with more than 0.2 gr/m^3 can thereby be detected at this range. This is confirmed by recent observations.

The Doppler performance of the radar is obtained through implementation of a coherent oscillator technique (COHO) in which the COHO is phase locked to the transmitter pulse signal. The phase locking is conveniently performed in the radar IF circuits with the phase coherent frequency transfer of the 94 GHz signals to a 60 MHz IF frequency done using a frequency stable source (STALO) as the local oscillator.

In the present version, phase coherent radar echo processing is performed in real time by a hardwired processor evaluating signal autocovariance (pulse-pair technique) at 256 range gate positions spaced by 400 ns (equivalent to 60 m in range). The real, A, and imaginary, B, terms of the autocovariance function are calculated and recorded in real time; the mean Doppler frequency $f_d = \{\tan^{-1}(A/B)\}/(2\pi\tau)$, as well as the spectrum width, are evaluated off-line using a minicomputer. The processor also evaluates the mean signal intensity from integration of the signal at the output of a logarithmic amplifier. The individual autocovariance terms are recorded on magnetic tape. The mean Doppler velocity, Doppler spectrum width and mean signal intensity are calculated by an off-line computer and plotted as range profiles.

We also have started to design another processing unit for the computing of complete Doppler spectra at a limited number of range gates. The design is based on storing the I and Q coherent video signals in a computer disc memory at the maximum transfer rate of a PC-AT (approximately 140 kbytes/second), allowing that the I and Q signals at 7 range gates be continuously recorded at a 10 kHz PRF frequency. The signals can be continuously loaded in the hard disc but, at this rate a 20 Mbyte hard disc will only hold 2 minutes of data.

Real time computation of the spectra can be done in real time using a hardwired card in the AT computer. The nominal time for the computation of a 1024 complex points power density spectrum is approximately 10 ms. Therefore, at the 10 kHz PRF operation, real time operation may be continuously possible at the 7 range gates. Loading the data at a higher rate or higher speed calculation of the Doppler spectra is certainly possible but would require much more expensive equipment which is beyond the scope of the research. We have rather decided to compromise by recording or possibly processing only 4 to 7 gates. The ensemble of range gates at which complete Doppler spectra can be evaluated can be sequentially displaced using a gate scanning logic to cover a greater radar range. Nevertheless, the new processor will always be operated in conjunction with the real time autocovariance estimator providing backup information on mean Doppler and spectral width, continuously at range gates spaced by 400 ns up to a maximum range of 15 km.

4.b.2. Backscattering and absorption of 94 GHz radiation.

The scattering and absorption of 94 GHz radiation by hydrometeors was investigated and the results applied to cloud and precipitation were published in [1] and [5].

The most important feature of the backscattering functions at 94 GHz is that the Mie solution exhibits deep oscillations within the precipitation particle size range. In a vertically pointing mode, the Doppler spectrum is the spectral distribution of scattered power as a function of the particle vertical velocity and therefore the particle size. The presence of up or down motion is associated with a shift of the whole spectrum and does not modify its shape. The Mie oscillations should thus be always noticeable in the Doppler spectrum shape and should indicate particle size at the same time as actual particle vertical velocity is identified in the Doppler spectrum. Comparing a Doppler spectrum observed at 94 GHz to another one observed at microwave wavelength for which Rayleigh scattering applies to the whole spectrum regardless of the particle size should provide means for accurate identification of both particle size distribution and vertical air velocity. These considerations are discussed in [7].

4.b.3. Observations

The research effort included observation of clouds and precipitation, analysis of some of the data, and publication of the results.

Most of the observations were performed in a vertically pointing mode using a 10 kHz pulse repetition rate and 256 range gates spaced by 400 ns (60 m range interval). The unambiguous velocity domain for that pulse repetition rate at the 3 mm wavelength is $\pm$ 8 m/s. The 3-second signal dwell time is acceptable for a fixed vertically pointing beam mode of observation and leads to accurate measurements of signal intensity and mean Doppler (and even spectral width if noise removal techniques are used [3]). With a Doppler spectrum width of 1 m/s the estimated statistical uncertainty of the mean Doppler measurement is approximately 1 cm/s which represents a significant improvement over microwave Doppler radar operation. Most of this velocity accuracy improvement is due to the very large number of samples available for the calculation of the estimates, resulting from the combination of a high PRF and a long dwell time which is acceptable in a fixed beam operation.

As mentioned above, the long signal dwell time also provides an effective signal to noise ratio gain of 20 to 25 dB so that a target with a reflectivity factor of -40 to -45 dBZ is detected by the radar at a 5 km range and the mean target Doppler velocity effectively measured. Some of the results of cloud and precipitation observations performed by the millimeter wave radar are described in the papers written in fulfillment of this contract and assembled in the attached document "94 GHz Doppler radar" mentioned above. These papers cover the following observations:

4.b.3.i. Cirrus clouds

The radar appears as an excellent detector of cirrus clouds even those which are tenuous and hardly seen by the naked eye. Radar reflectivity of cirrus clouds was observed to vary from less than -40 dBZ (minimum detectable reflectivity at 10 km) to more than -25 dBZ. The vertical velocity of cirrus cloud particles was measured as ranging from more than 2 m/s to less then 0.5 m s^{-1}. Upward motion was sometimes observed (primarily at the cirrus top) [3].

4.b.3.ii. Clouds

Very few observations were made on small cumulus clouds. However, we have recently initiated a program of systematic observation of such small clouds which has shown that small cumulus even with a vertical development not exceeding a few hundred meters to a kilometer were effectively detected by the Doppler radar and the particle vertical velocity measured. As an example, a radar reflectivity varying from -50 dBZ (minimum detectable at 1 km) to -35 dBz was measured for cumulus with less than 500 meters vertical development (indicated by the vertical depth of the radar echo). Note that -40 dBz is the radar reflectivity of a cloud with approximately 0.1 g/m^3 and 10-15 μ median droplet diameter.

4.b.3.iii. Convective storms

Only the top of thunderstorms could be observed if they are at more than 10-20 km range. This is due to the fact that for low radar beam elevation angle the atmospheric absorption due to atmospheric water vapor is prohibitive (such as 40 dB two-way for a 15° elevation angle. These absorption values are considerably reduced for greater elevation angles allowing that the top of thunderstorms be detected by the millimeter wave radar [3].

4.b.3.iv. Bright band in stratified clouds

The expected accuracy of radial velocity measurements obtained with the Doppler radar was demonstrated in the observation of very stable vertical profiles of mean vertical velocity observed in stratified, stable conditions associated with the presence of a well-defined "bright band". These observations are discussed in detail in [3] and [6].

4.b.4. Conclusion

This research has definitely established the usefulness of the millimeter wave Doppler radar for the study of small cloud kinematics. The recent successful observation of droplets' vertical velocity in small fair weather type cumulus has been a landmark in our research. These data are now being analyzed. So far, the results have shown that a well-organized updraft-downdraft structure is observed. We are now confident that the radar will emerge as an essential tool for the study of the early stages of convective clouds development.

The concept and design of the Doppler radar has proven satisfactory. We are now planning to improve the signal processing methods to include processing of complete spectra. We also intend to equip the radar with only one antenna using a newly designed TR switch which will greatly facilitate housing of the radar either in a small van or aboard an airplane.

4.c. List of all publications and technical reports published

[1]. Lhermitte, R.M., 1981. Millimeter Wave Doppler Radar, Proc. 20th Conference on Radar Meteor., Am. Meteor. Soc., 744-748.

[2]. Lhermitte, R. and C. Frush, 1984. Millimeter Wave Radar for Meteorological Observations, Preprint Volume: 22nd Conference on Radar Meteorology, Sept. 10-13, 1984, Zurich, Switzerland, Am. Meteor. Soc., 228-231.

[3]. Lhermitte, R.M., 1986. A 94 GHz Doppler Radar for Cloud Observations. J. Atmos. Ocean. Tech. (in press).

[4]. Lhermitte, R.M., 1986. Absorption and Scattering by Clouds and Precipitation at 94 GHz. Presented at the Airborne Doppler Meeting, July 8-9, 1986, Boulder, CO.

[5]. Lhermitte, R., 1986. A 3 mm wavelength Doppler Radar for Meteorological Observation. International Union of Radio Science. Commission F. Wave Propagation and Remote Sensing, Preprint Volume, Open Symposium, July 28 - August 1, 1986, Durham, New Hampshire, 6.7.1 - 6.7.4.

[6]. Lhermitte, R.M., 1986. Observation of Clouds and Precipitation Using a 94 GHz Doppler Radar. Presented at the Workshop on Ground Based Remote Sensing of the Troposphere, 25-28 August, 1986, Hamburg, Germany.

[7]. Lhermitte, R.M., 1986. Cloud and Precipitation Observation with 94 GHz Doppler Radar. Proceedings of Cloud Physics and Radar Conference, Snowmass Village, CO, Setpember 21-27, 1986.

4.d. Participating Scientific Personnel

Mr. Henry Poor, Research Associate

5. Bibliography (same as 4.c)

6. Appendix - 94 GHz Doppler radar project volume

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