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WIND GRADIENTS AND VARIANCE OF DOPPLER SPECTRA*

Louis J. Battan
Institute of Atmospheric Physics
and
John B. Theiss
Engineering Research Laboratory

Tucson, Arizona

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ABSTRACT

An X-band pulsed-Doppler radar having its beam fixed at an elevation angle of 3 deg, was used to measure radial velocity spectra in a light shower. Observations were made at intervals of 152 m between radar ranges of 7 and 18 km. It was found that the mean Doppler velocity, variance of the Doppler spectrum and radar reflectivity varied markedly over distances of the order of 100 m. The observed variance was below about 1 $m^2 sec^{-2}$ in 80 percent of the observations, but in about 4 percent of the cases, it exceeded 3 $m^2 sec^{-2}$. An analysis of $\Delta V/\Delta r$, the radial gradient of the mean Doppler velocity yielded a nearly Gaussian curve having a mean of 0.2×10^{-3} sec^{-1} and a standard deviation of 5.9×10^{-3} sec^{-1}. The largest value observed was 3×10^{-2} sec^{-1}. The effects of the radial gradient of the radial wind apparently can explain about 25 percent of the observed variance of the Doppler spectrum.

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Louis J. Battan and John B. Theiss
The University of Arizona
Tucson, Arizona 85721

It is well known that the variance of the Doppler spectrum obtained when a suitable radar observes precipitation depends on the following factors: (1) the motion of scatterers across the beam; (2) wind shear; (3) small scale turbulence; (4) the components along the beam axis of the terminal velocity spectrum of the scatterers (Hitschfeld and Dennis, 1956; Rogers, 1957; Lhermitte, 1963; Atlas, 1964 and others).

If a radar set employs a narrow beam and examines precipitation at short ranges, the motion of particles perpendicular to the beam axis has little effect on increasing the variance of the Doppler spectrum. This point was noted by the authors already cited and most recently has been verified by Sloss and Atlas (1968). When the radar antenna is pointing towards the zenith, the other three factors must be considered. If the effects of wind shear and small scale turbulence are negligibly small, the mean Doppler velocity and variance will depend only on the properties of the scattering particles and the vertical motion of the air in the volume of air being observed. In some such circumstances, the positive velocity bound (upwards) of the Doppler spectrum may be used to indicate the updraft velocity in the manner reported by Battan and Theiss (1970). On the other hand, as emphasized by Donaldson and Wexler (1969) the presence of wind shear and small scale turbulence, if sufficiently large, can increase the variance of the Doppler spectrum and lead to incorrect inferences about updraft velocities.

Early measurements of gustiness in precipitation by Rogers (1957) had led to the assumption that the effects of turbulence would not contribute more than perhaps 0.5 m^2/sec^2 to the variance. Donaldson and Wexler (1969) on the basis of Doppler radar measurements in a thunderstorm concluded that sometimes, in the presence of strong shear of the updraft, the variance can be increased by many m^2/sec^2. They reported that at least 5 percent of their measurements of variance were too large to be accounted for by the spread of the precipitation fall speeds or vertical gradient of the vertical air velocity, and hence they concluded that variance was increased by small scale turbulence and possibly wind shear.

In this paper, an analysis has been made of some new Doppler radar observations in an attempt to identify some factors contributing to the variance of the Doppler spectrum.

Observations

The X-band pulsed-Doppler radar previously described by Battan and Theiss (1970) was employed to measure horizontal variations of radar backscattering in a shower occurring near Tucson, Arizona on 25 August 1969. The radar beam was fixed at an elevation angle of 3°, and observations were obtained of radar reflectivities and Doppler spectra, at range intervals of about 152 m, through a light shower located at distances between 7 and 18 km from the radar.

Calculations were made of mean Doppler velocity and variance of each spectrum. The resulting patterns are shown in Figs. 1 and 2. The grid points used for constructing these diagrams were separated by 152 m in range and about one minute in time. Certain aspects of these illustrations will be discussed in a later part of this paper. At this time, we wish to call attention to the measurements of mean Doppler velocity and variance. The outstanding features are the pronounced regions of maxima of both. The location of the maxima appear to be related. This point will be examined in due course.

The diagram showing the variance of the Doppler spectra shows surprisingly large values, particularly at ranges between about 12 and 17 km. Earlier, Lhermitte (1969) also observed large variances when viewing rainfall with a horizontally oriented radar beam. Precipitation-particle fall velocities should have little effect at these ranges considering the 1.3° beam width. It must be concluded that wind gradients and small scale turbulence account for the large variances. In this regard, it is appropriate to note that these observations confirm the conclusions advanced earlier by Donaldson and Wexler (1969) that, sometimes, factors other than the spread of the particle fall speeds can have a pronounced effect on the variance and spread of the Doppler spectrum.

The relative frequency of various values of the variance for the two records (where the designations I and II correspond to Fig. 1 and 2, respectively) are shown in Fig. 3. It is evident that about 80 percent of the time, the variance was less 1 m^2/sec^2. On the other hand, in about 4 percent of the cases, it exceeded 3 m^2/sec^2, and it sometimes exceeded 6 m^2/sec^2.

Figure 4 shows the relative frequency of measured variance in three circumstances:

a) horizontally pointing antenna examining rain;

b) zenith pointing antenna examining a thunderstorm;

c) zenith pointing antenna examining a storm yielding hail as large as about 2.5 cm in diameter.

The differences between the first two curves are small, amounting to about 1 m^2/sec^2 and probably can be accounted for by considering the fall speeds of raindrops. The variances in the hailstorm were substantially larger than in the other two cases as would be expected in view of the large sizes and high terminal speeds of hailstones.

Analysis

The data collected during the period 1535 to 1544 MST, shown in Fig. 2 were analyzed in an attempt to account for the patterns of variance. There is a slight indication that the regions of large variances are associated with relatively high radar reflectivities (10 log Z), but overall the relationship is poor. On the other hand as noted earlier, high values of variance appeared to be associated with high values of the radial wind component. A closer examination shows an association of the variance with the radial gradient of the radial wind. The latter quantity is depicted in Figs. 1 and 2 and identified as $\Delta V/\Delta r$ where V is the mean Doppler velocity.

The frequency distribution of quantity $\Delta V/\Delta r$ is given in Fig. 5. It is sharply peaked at a value just below zero. The mean and standard deviation of the distribution which is close to Gaussian are 0.18×10^{-3} and 5.9×10^{-3} respectively. About 78, 94 and 98 percent of the observations were within plus and minus 1, 2 and 3 standard deviations respectively. Although the largest value was -30×10^{-3} $\sec^{-1}$, there were slightly more positive values of the gradient.

Lhermitte (1963) derived an expression for calculating the effect of radial wind gradient on the variance. For the conditions in this analysis the equation reduces to

$$\sigma_V^2 = 8.7 \times 10^{-10} \left(\frac{\Delta V}{\Delta R}\right)^2 r^2 \qquad (1)$$

when the quantities $\Delta V/\Delta r$ and r are in units of m/sec and m, respectively. Calculations of σ_V^2 were made for each series of radial observations for $\Delta r = 152$ m. The resulting pattern of σ_V^2 is shown in Fig. 2. It can be seen that in general, the regions where the calculated variance was large coincided with regions where the observed variance was high. Also the calculated values ascribable to radial gradient of the radial component of the wind were of the same order as the observed variances. At the same time, it should be noted that sometimes there were substantial differences between the calculated and observed quantities.

The correlation coefficient between the observed variance and the calculated variance was 0.5, a highly significant quantity considering the fact that there were 588 independent samples. This result indicates that radial gradient of the radial wind component clearly accounts for part of the observed variance of the Doppler spectrum. Nevertheless, the correlation coefficient of 0.5 indicates that it accounts for only 0.25 of the observed total variance. Presumably the remaining 0.75 is a result of wind shear across the beam and small scale turbulence.

The results of this analysis indicate, as was proposed earlier by Donaldson and Wexler (1969), that the scheme of inferring updraft speeds by means of the positive bound of the Doppler spectrum can sometimes be seriously in error. Most of the time, perhaps 80 percent or more, the errors are likely to be less than 1 m/sec, but in those areas of strong gradients of air motion, in the vicinity of strong cores of updrafts or downdrafts the spreading of the Doppler spectrum may amount to several meters per second.

It is unfortunate that only one component of the wind could be observed and related to the variance of the Doppler spectrum. By means of two Doppler radars in the manner used by Lhermitte (1970) it would be possible to relate the variance to shear of the horizontal wind velocity. Ultimately it needs to be related to the shear of the three-dimensional air velocity.

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LEGENDS FOR FIGURES

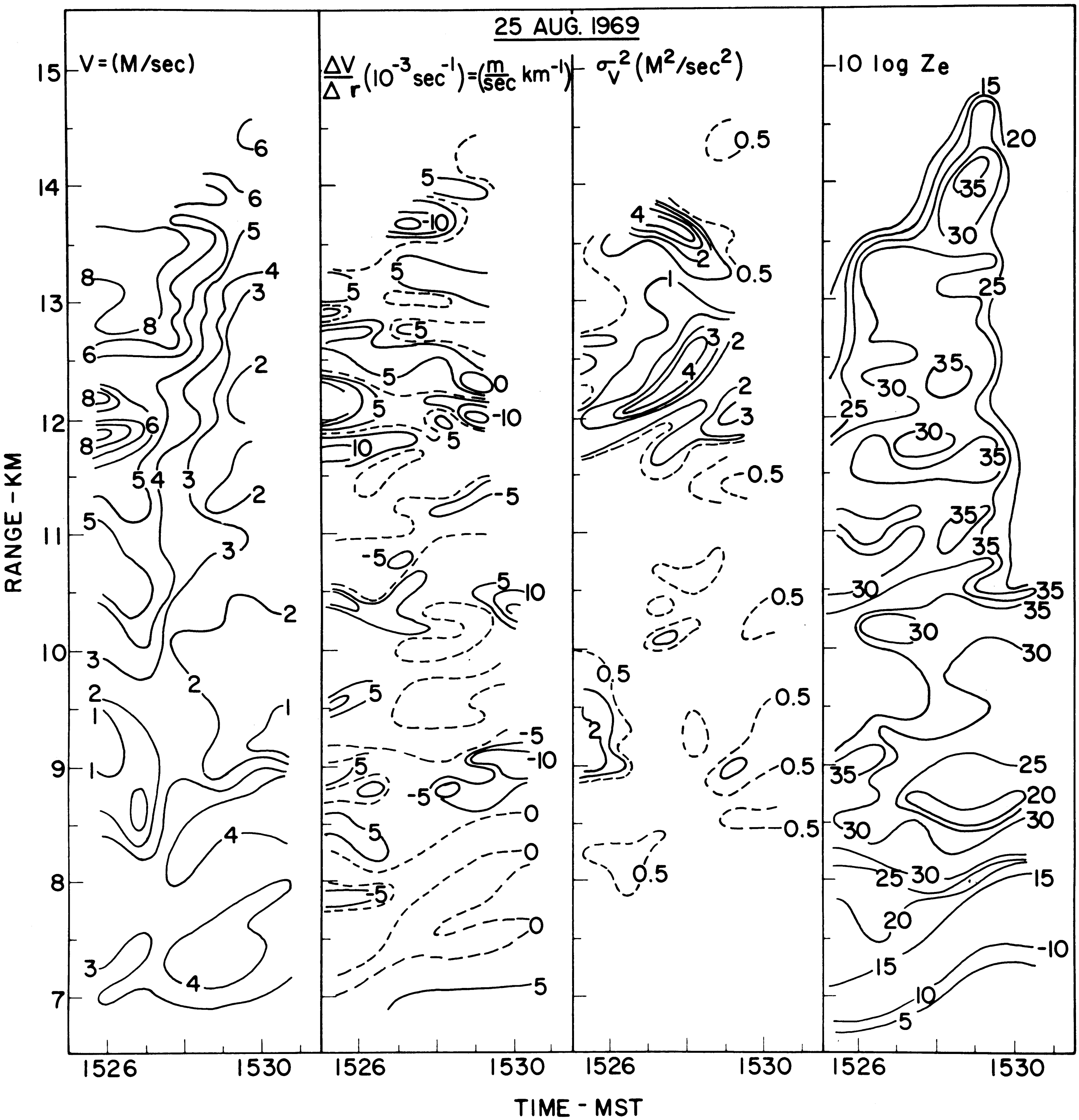
Fig. 1 Time *versus* radar-range profiles of various properties of a light shower obtained by means of an X-band pulsed-Doppler radar having its antenna fixed at an elevation angle of 3°. V is the mean Doppler velocity; $\Delta V/\Delta r$ is the radial gradient of V when Δr was 152 m; σ_V^2 is the variance of the Doppler spectrum; Z_e is the effective radar reflectivity factor in units mm^6/m^3.

Fig. 2 Same as Fig. 1 for the time period 1535-1544 MST except for the addition of profiles of σ_V^2 calculated by means of $\sigma_V^2 = 8.7 \times 10^{-10} \left(\frac{\Delta V}{\Delta R}\right)^2 r^2$.

Fig. 3 Cumulative frequency distributions of observed variance. The numbers I and II correspond with the data in Figs. 1 and 2, respectively.

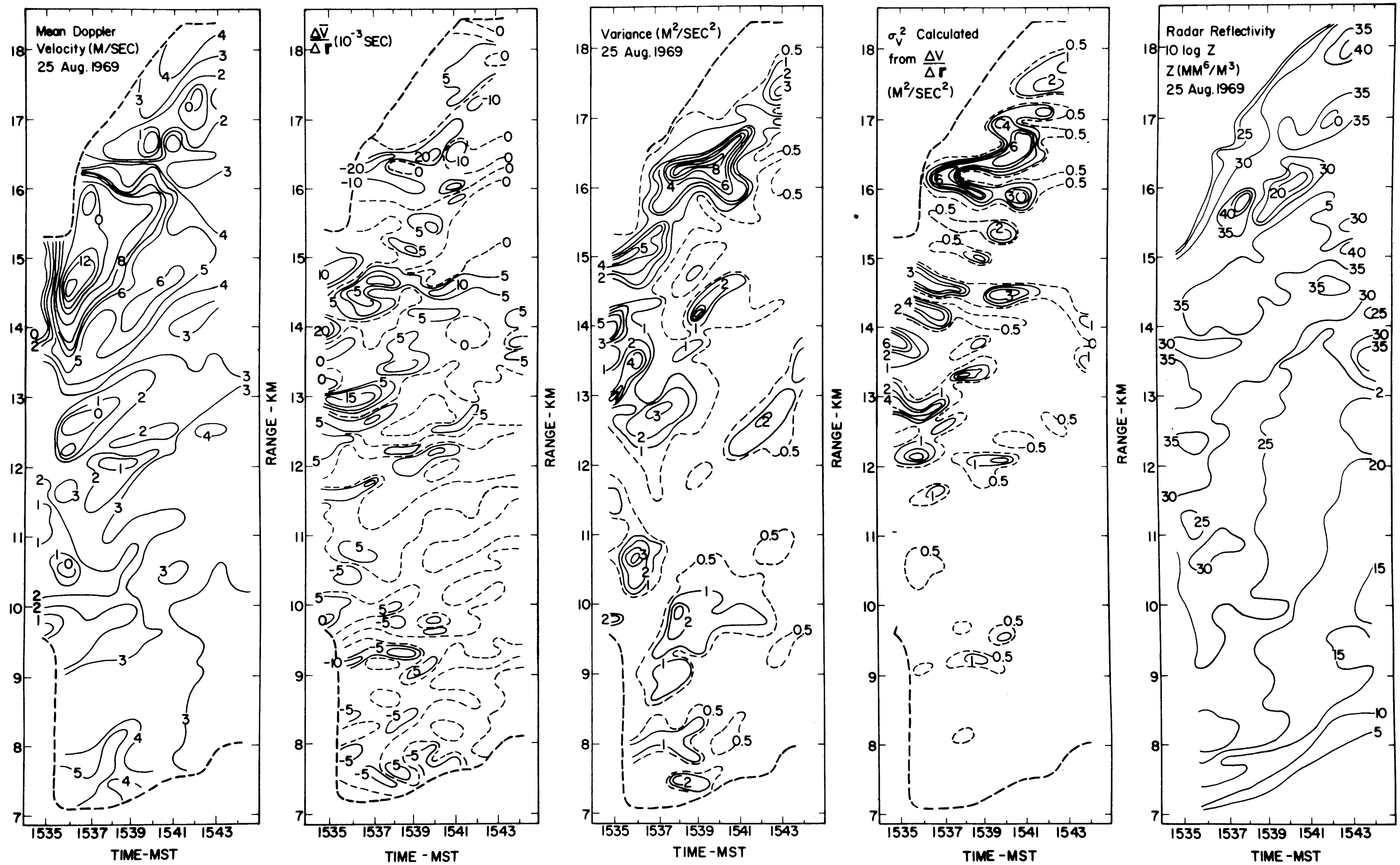
Fig. 4 Cumulative frequency distributions of observed variance in various circumstances.

Fig. 5 Frequency distribution of $\Delta V/\Delta r$ in units of 10^{-3} sec^{-1} observed during the two periods shown in Figs. 1 and 2.



25 AUG. 1969
V = (M/sec)
ΔV/Δr (10⁻³ sec⁻¹) = (m/sec km⁻¹)
σV² (M²/sec²)
10 log Ze
RANGE - KM
TIME - MST
1526
1530

Figure 1



Mean Doppler Velocity (M/SEC) 25 Aug. 1969
$\frac{\Delta \bar{V}}{\Delta r}$ (10^{-3} SEC)
Variance (M^2/SEC^2) 25 Aug. 1969
σ_V^2 Calculated from $\frac{\Delta V}{\Delta r}$ (M^2/SEC^2)
Radar Reflectivity 10 log Z Z (MM^6/M^3) 25 Aug. 1969
RANGE - KM
TIME - MST

Figure 2

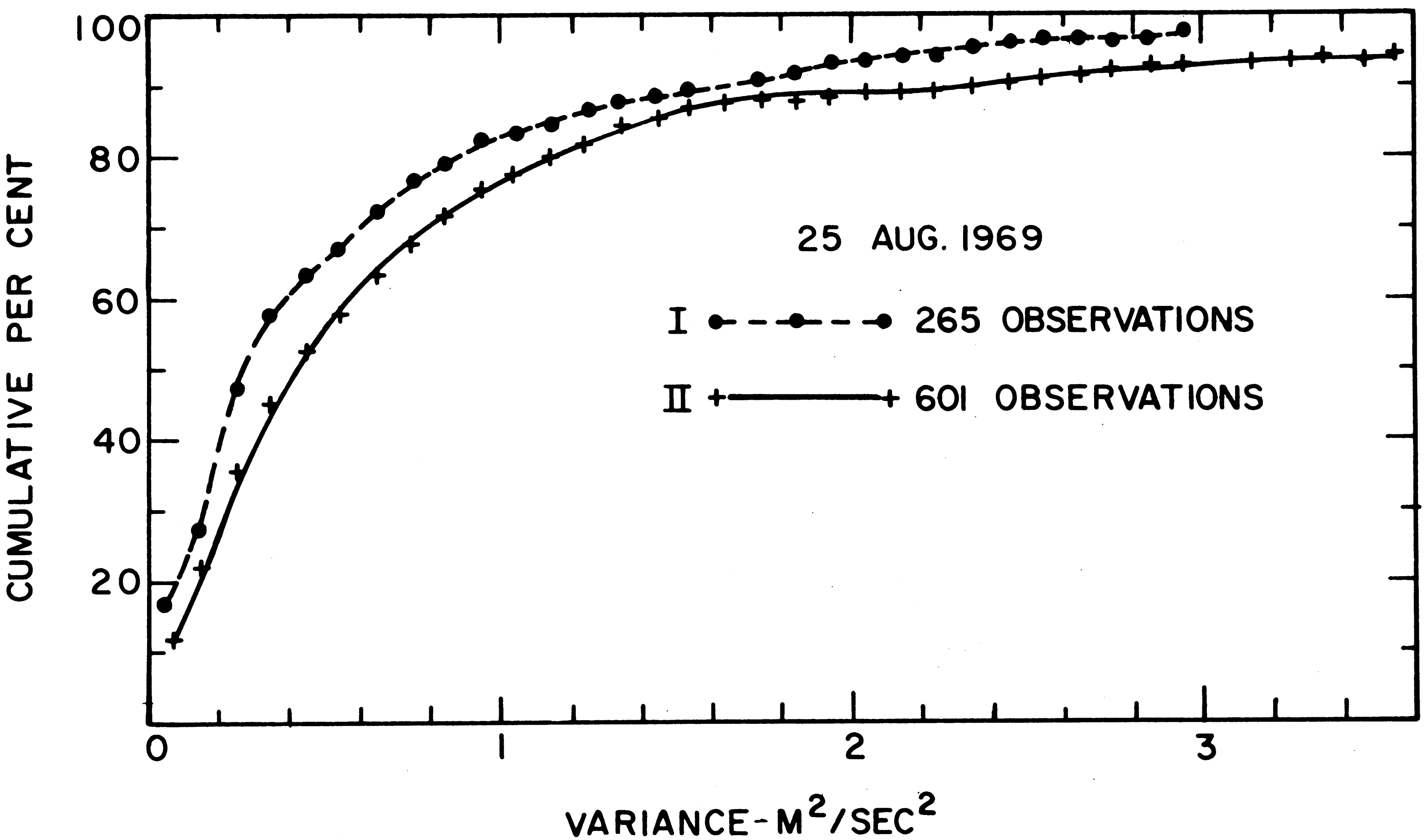
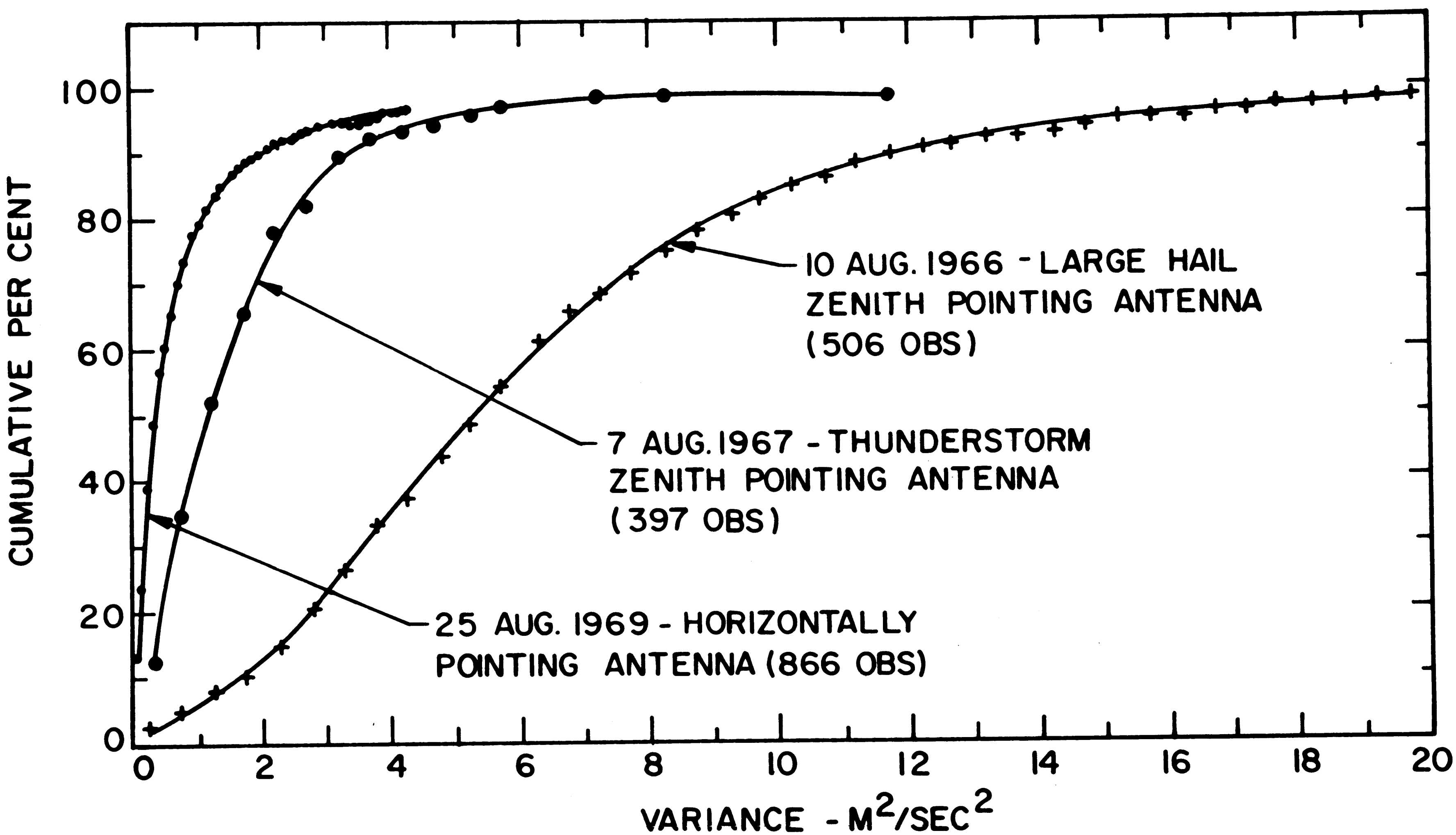

100
80
60
40
20
0
1
2
3
CUMULATIVE PER CENT
VARIANCE-M2/SEC2
25 AUG. 1969
I 265 OBSERVATIONS
II 601 OBSERVATIONS

Figure 3



CUMULATIVE PER CENT
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20
VARIANCE - M^2/SEC^2
10 AUG. 1966 - LARGE HAIL
ZENITH POINTING ANTENNA
(506 OBS)
7 AUG. 1967 - THUNDERSTORM
ZENITH POINTING ANTENNA
(397 OBS)
25 AUG. 1969 - HORIZONTALLY
POINTING ANTENNA (866 OBS)

Figure 4

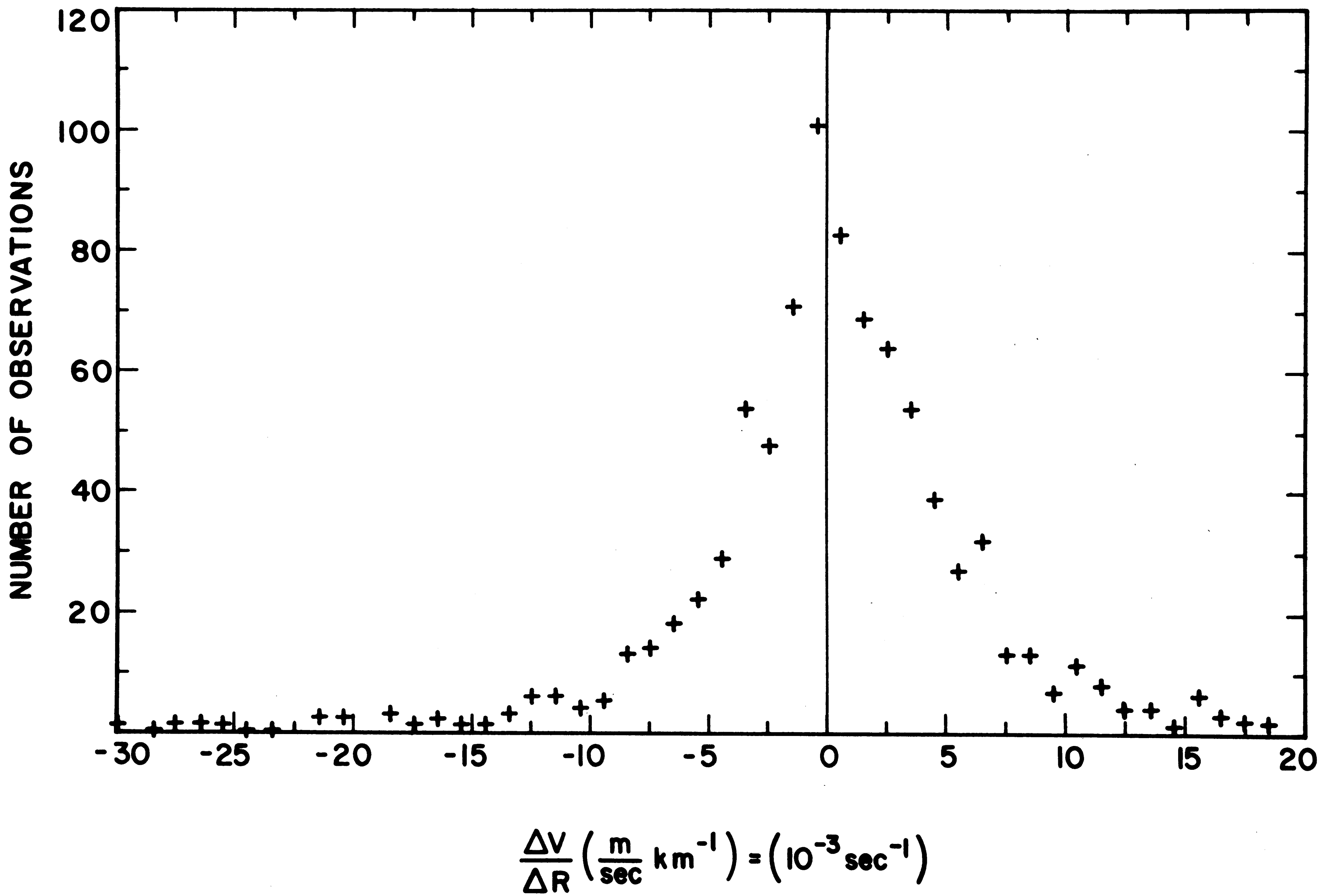

120
100
80
60
40
20
NUMBER OF OBSERVATIONS
-30
-25
-20
-15
-10
-5
0
5
10
15
20
$\frac{\Delta V}{\Delta R}\left(\frac{m}{sec} km^{-1}\right) = \left(10^{-3} sec^{-1}\right)$

Figure 5