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Radio acoustic measurement of temperature profile in the troposphere and stratosphere

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The radio acoustic sounding system (RASS) uses radar to measure the temperature profile in the atmosphere. In the standard technique of atmospheric radar, the radar backscatter results from electrical permittivity variations due to natural phenomena such as turbulence and precipitation. In the RASS technique, the radar backscatter results from periodical permittivity variations due to density/temperature variations imposed on the atmosphere by an acoustic wave artificially generated in such a way that the acoustic wavelength is half the radar (electromagnetic) wavelength. This 'Bragg condition' is necessary for efficient backscattering. The backscatter echo of the RASS is affected by the Doppler frequency shift arising both from the speed at which the longitudinal acoustic perturbations propagate (the sound speed), and from the radial bulk velocity in the common volume of the atmosphere—the latter can be measured by the standard technique of turbulence scatter. The observed sound speed is reduced to give the local atmospheric temperature. Here we report an experiment using the RASS, carried out on 1–3 August 1985, which consisted of a high-power, very-high-frequency (VHF) Doppler radar at Shigaraki, Shiga, Japan and a movable high-power acoustic transmitter, and which gave the first experimental proof of the possibility of temperature profiling in the troposphere and stratosphere up to an altitude of ~20 km.

Researches on RASS, initiated by Marshall *et al.*[1], have been advanced during the past decade by several groups [2-4] in various countries, who have concentrated on atmospheric temperature measurements in the planetary boundary layer up to ~2 km above the ground. Most of these experiments used a RASS consisting of an ultra-high-frequency (UHF) Doppler radar and an acoustic transmitter at frequencies ≥1 kHz. The altitude ranges for which the temperature measurements in these experiments were successful lie mostly below ~1 km, with an upper limit at 3 km. The present experiment was designed to measure the higher atmosphere, up to the level of the stratosphere. To achieve this, our RASS comprises a monostatic pulsed Doppler radar in the VHF range (the MU radar[5,6]), completed in November 1984 at Shigaraki by the Radio Atmospheric Science Center of Kyoto University, and a pneumatic acoustic transmitter at frequencies of ~100 Hz provided by the Radio Research Laboratory. Atmospheric absorption of such a low-frequency acoustic wave is less effective, and the acoustic wave may propagate to an altitude of ~30 km without any appreciable attenuation caused by atmospheric absorption. The operational parameters for the MU radar and the acoustic transmitter used in the present experiment are given in Table 1.

For the RASS to attain an efficient radar backscatter from the periodical permittivity variations imposed by an acoustic wave requires that, for monostatic radars, the acoustic wavenumber vector $\mathbf{K}_a$ $(\equiv 2\pi\mathbf{k}_a/\lambda_a)$ has to be equal to twice the wavenumber vector $\mathbf{K}_r$ $(\equiv 2\pi\mathbf{k}_r/\lambda_r)$ for the primary radar wave; that is, $\mathbf{K}_a \simeq 2\mathbf{K}_r$ at the scattering point, where $\mathbf{k}$ is the unit vector of the wave normal and λ is the wavelength, with suffixes a and r denoting the acoustic and radar waves, respectively. This Bragg condition is equivalent to two conditions: the 'wavelength condition' that $2\lambda_a \simeq \lambda_r$, and the 'wave-vector condition' that $\mathbf{k}_a \simeq \mathbf{k}_r$ or the angle between the two vectors $\cos^{-1}(\mathbf{k}_a \cdot \mathbf{k}_r) \simeq 0$. The power of the backscattered echo is fairly sensitive to both conditions, so that, for the present experiment, the echo power may be reduced to about one tenth of that expected in the ideal case by a deviation in the 'wavelength condition' such that $2\lambda_a/\lambda_r = 1 \pm 0.015$ (where the number of wavelengths in the acoustic pulse $n_a = 100$) or by a deviation in the 'wave-vector condition' such that $\cos^{-1}(\mathbf{k}_a \cdot \mathbf{k}_r) = 0.3°$ (where the distance to the scattering point from the radar site is assumed to be 10 km). It is unlikely that the RASS satisfies both conditions ideally, but it is reasonable to expect that the two conditions can be approximately satisfied.

Table 1 Major operational parameters of the RASS

MU radar (monostatic pulsed Doppler radar)	
Frequency (MHz)	46.5
Antenna aperture (m^2)	8,330
Antenna gain (dB)	33
Beam-width (deg.)	3.6
Peak power (MW)	1
Sub-pulse-width (μs)	2
Pulse compression (bits bi-phase coding)	8
Pulse repetition (pulses per second)	2,400
Acoustic transmitter (pneumatic acoustic generator)	
Frequency (Hz)	88–102
Acoustic power (W)	100
Antenna	Exponential horn
Antenna gain (dB)	10
Beam-width (deg.)	45
Pulse-width (s)	1
Pulse repetition (pulses per hour)	16

In the present experiment, the radar wavelength λ_r is constant (at 6.45 m) and the radar wave-vector $\mathbf{k}_r$ is always in the radial direction along the radar beam (beam-width 3.6°), which is steerable in the zenith-angle range between 0° and 30° for the whole azimuth. On the other hand, the acoustic wavelength λ_a and wave-vector $\mathbf{k}_a$ vary along the propagational path under the influence of various atmospheric conditions. The acoustic wavelength at a frequency f_a varies with altitude due to the variation in atmospheric temperature and hence in the local sound speed, $c_a(=\lambda_a f_a)$. Therefore, it is necessary to transmit the acoustic pulses at different frequencies in order to meet the 'wavelength condition' at a wide range of altitudes. In the present experiment, the frequency of the acoustic wave was changed from pulse to pulse in the range between 88 and 102 Hz, with a frequency step of 1 or 2 Hz. The propagational path of an acoustic wave is affected by refraction due to the existence of a vertical gradient in atmospheric temperature, and also by atmospheric bulk motion due to winds and turbulence. A transmitted acoustic wave consists of various rays whose angles of incidence are distributed over a comparatively wide range of directions (the acoustic beam-width for the present RASS is ~45°). In the simplest case, when there is a vertical gradient in the atmospheric temperature but no atmospheric bulk motion, the acoustic ray of vertical incidence may satisfy the 'wave-vector condition' in association with the radar beam of vertical incidence, provided that both waves are transmitted from the same place. The acoustic rays of oblique incidence refract upwards, and their paths are no longer in the radial direction from the transmitter. When there are horizontal winds as well as a vertical gradient in temperature, it is necessary to choose a place for the acoustic transmitter on the windward side of the radar antenna and to vary the direction of the radar beam until it satisfies the 'wave-vector condition' at the altitude of interest. In the present experiment, the acoustic transmitter was moved to three appropriate positions within a few hundred metres on the windward side of the radar antenna, and the radar beam direction was swept in the zenith-angle range between 0° and 10° on both the windward and leeward sides, so that RASS echoes could be obtained from the troposphere and stratosphere.

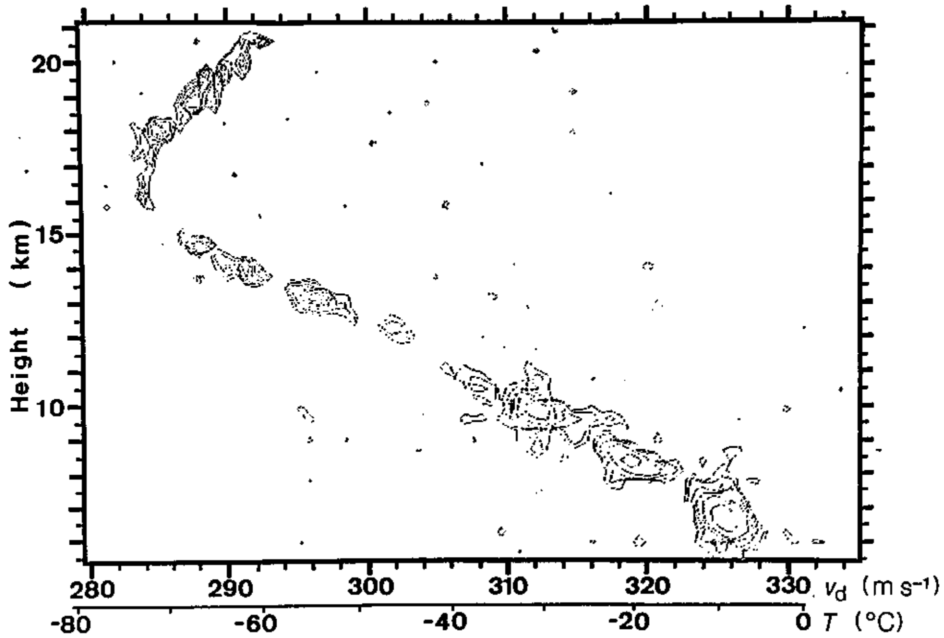

Fig. 1 Contours of RASS echo power spectra in the coordinates of height (resolution 300 m) versus Doppler velocity V_d (m s^{-1}) (resolution 0.6 m s^{-1}) and reduced temperature T (°C) (resolution ≈ 0.9°). A train of blobs in the spectral contours reproduced by a superposition of the data from individual soundings indicates the RASS echoes which are caused by acoustic pulses at discrete frequencies of 101, 99, 97, 95, 94, 92, 90, 89 and 88 Hz.

Examples of the Doppler power spectra acquired from the RASS experiment on 1-3 August 1985 are shown in Fig. 1, where a train of blobs in the spectral contours is reproduced by a superposition of the data from individual soundings. Each blob from right to left indicates the RASS echo caused by passage of the acoustic pulse at each of the nine discrete frequencies, 101, 99, 97, 95, 94, 92, 90, 89 and 88 Hz. The power spectra were obtained by means of fast Fourier transform analyses with an integration time of 3 s, Doppler frequency resolution of 0.2 Hz or Doppler velocity resolution of 0.6 m s^{-1}, and height resolution of 300 m. In Fig. 1, the temperature is reduced from the Doppler velocity V_d (m s^{-1}) by the relation $T(°C) = V_d^2/(\gamma R/M) - 273.2$ (assuming a dry atmosphere without wind), where γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume, R is the universal gas constant (8.314×10^3 J mol^{-1} K^{-1}) and M is the mean molecular weight of the atmospheric gas. The temperature error arising from the presence of water vapour in the atmosphere is ≤1 °C. The ratio of the peak echo level at the centre of each blob in Fig. 1 to the background noise level is estimated to lie in the ranges 27-20 dB, 18-10 dB and 14-11 dB, for the groups of the blobs belonging to the altitude ranges <10 km, 10-15 km and 15-20 km, respectively. The peak level as well as the spectral pattern of the RASS echo blob varies from blob to blob. The Doppler frequency arising from the speed of sound, f_d $(= 2\lambda_a f_a/\lambda_r)$, measured at the centre of each blob is not always equal to the frequency f_a of the acoustic wave causing each of the RASS echoes. These facts suggest that the power spectra of the RASS echo is under the influence of a delicate balance between the effects of the 'wavelength condition' and the 'wave-vector condition', and that the perfect 'wavelength condition', $2\lambda_a = \lambda_r$, is not necessarily satisfied at the centre of the RASS echo blob. Therefore, the Doppler technique is effective for an accurate measurement of the sound speed. In addition, the fine frequency resolution by the Doppler technique results in an efficient detection of the RASS echo, which has a higher signal-to-noise ratio.

In Fig. 2, the central heights of all the blobs in the power spectra of the RASS echoes obtained on 1-3 August 1985 are plotted against temperature, where the height is corrected to that above sea level and the temperature is reduced from the measured Doppler velocity V_d by the relation, $T(°C) = (V_d - W \sin \chi)^2/(\gamma R/M) - 273.2$, where the effect of horizontal wind in the direction of the radar beam azimuth, W (m s^{-1}), measured from the standard technique of turbulence scatter, are

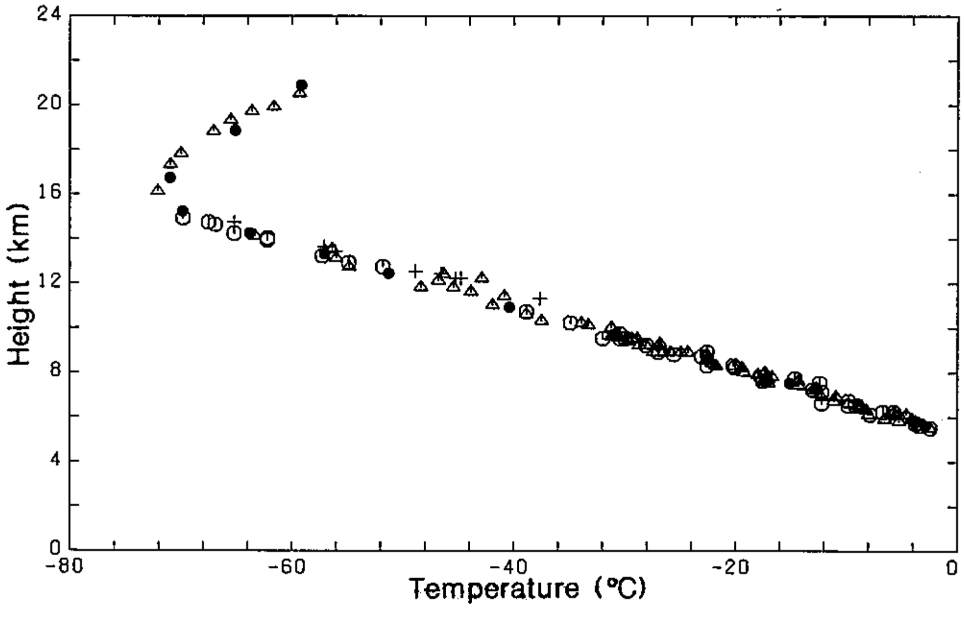

Fig. 2 Temperature profile reduced from all of the RASS echoes observed on 1-3 August 1985 at three different radar-beam zenith angles ($\chi = 0°$ (O), 5° (Δ) and 10° (+)), where the height is corrected to the value above sea level and the temperature is reduced from the Doppler velocity excluding the wind component. ●, Temperature profile from the radiosonde measurements at Shionomisaki.

compensated and χ is the zenith angle of the radar beam. The temperature profile from the present RASS experiment agrees reasonably well with the average temperature profile from the radiosonde measurements by the Japan Meteorological Agency at Shionomisaki, ~157 km south of the Shigaraki radar site (see Fig. 2).

Comparison between the vertical thermal profiles measured by the present RASS and by the radiosonde system demonstrates that the RASS can measure thermal profiles up to an altitude of at least ~20 km with an accuracy and vertical resolution comparable with the radiosonde technique, with the additional advantages of a possible rapid succession of measurements and a comparatively low cost of operation. The RASS technique effectively complements the capabilities of VHF radars, such as the measurement of winds, waves and turbulence, and other attempts to retrieve temperature profiles from such radar measurements by using the measured Brunt–Väisälä frequency.

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