References and Notes

1. A. Einstein, *Ann. Phys.* **49**, 769 (1916).
2. See, for example, H. Klüber, in *Vistas in Astronomy* (Pergamon Press, London, 1960), vol. 3, p. 47.
3. H. Hill and C. Zanoni (personal communication) are, however, developing different daytime astrometry techniques at optical wavelengths which show high promise.
4. This experiment is complementary to, but philosophically distinct from the radar time-delay test of general relativity proposed by I. Shapiro [*Phys. Rev. Lett.* **13**, 789 (1964)].
5. See, for example, A. S. Eddington, *The Mathematical Theory of Relativity* (Cambridge University Press, 1960), p. 93.
6. ———, *ibid.*, p. 87.
7. M. C. Thompson, Jr., H. B. Janes, W. B. Grant, in preparation.
8. The (uncorrected) elevation-angle fluctuations are considerably greater (*7*), but the azimuth angle is the relevant quantity for detecting a solar gravitational deflection.
9. M. C. Thompson, Jr., personal communication.
10. See, for example, W. C. Erickson, *Astrophys. J.* **139**, 1290 (1964).
11. At 2×10^3 Mhz and below, effects of turbulence in the corona become discernible at solar distances up to about 10 r_s (R. B. Dyce and R. M. Goldstein, personal communications) and may make the deduction of plasma densities difficult.
12. P. E. Green, *J. Geophys. Res.* **65**, 1108 (1960).
13. A report on the problems involved in the actual processing of the planetary echoes to achieve the required resolution, as well as the role of atomic clocks in long base line interferometry, is in preparation.
14. M. E. Ash, I. I. Shapiro, W. B. Smith, *Astron. J.* **72**, 338 (1967).
15. If intercontinental base lines become feasible, perhaps at somewhat lower frequencies, then detection of continental drifts of the order of 1 cm per year might be possible. An island such as Puerto Rico, with its Arecibo radar facility, might be an ideal first choice for one arm of such an interferometer. Radio beacons or phase-coherent transponders on the moon or on synchronous earth satellites might be more appropriate than planetary targets for this purpose. With a source on the moon, high-accuracy studies of lunar libration and orbital motion would also be possible. The "geodesic precession" might be detectable as well.
16. M. C. Thompson, Jr., and H. B. Janes, in preparation.
17. Such interferometric measurements can, of course, also be used to improve orbit determinations.
18. M. C. Thompson, Jr., D. Smith, D. M. Waters, R. O. Gilmer, *National Bureau of Standards Report No. 9144* (1966, unpublished).
19. I. I. Shapiro, M. E. Ash, G. H. Pettengill, M. L. Stone, W. B. Smith, in preparation.
20. Unfortunately, the Haystack-Westford base line is nearly north to south and has its largest component along the most useful direction for detecting gravitational light deflection only near dawn and dusk when atmospheric effects are most severe.
21. T. Hagfors, personal communication.
22. "Objectives and study program for a regional radio and radar astronomy research facility" (Cambridge Radio Observatory Committee, 1965, unpublished).
23. Lincoln Laboratory is operated with support from the U.S. Air Force.

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Clear-Air Turbulence: Simultaneous Observations by Radar and Aircraft

Abstract. *Ultrasensitive radars and uninstrumented jet aircraft in concert have probed regions of the clear atmosphere in search of clear-air turbulence. All sources of clear-air radar echoes above 6 kilometers that were probed simultaneously by the aircraft were found to be turbulent.*

At Wallops Island, Virginia, ultrasensitive radars of 3.2-, 10.7-, and 71.5-cm wavelength are being used to investigate the nature of all radar echoes from a clear atmosphere. One object of the program is to determine the feasibility of using radar for detecting clear-air turbulence (CAT); such turbulence at high altitude has recently attracted attention by the government and the airlines. Aircraft accidents have been attributed to unexpected encounters with turbulence in cloudless skies. For increased safety and because of the high costs of damage to aircraft and of flying diversionary routes to avoid turbulence, a system for detecting turbulence from a distance is obviously desirable.

The Wallops Island radar facility has been described (*1*). Its more important characteristics for this discussion are the beamwidths of 0.21, 0.48, and 2.9 deg, and the minimum detectable signals of −110, −115, and −112 dbm (decibels referred to milliwatts) for the radars of 3.2-, 10.7-, and 71.5-cm wavelength, respectively. Using this multiwavelength facility, one can distinguish between clear-air radar echoes and echoes caused by clouds, precipitation, or any other types of particulate matter (*1, 2*). The clear-air echoes arise because of scattering caused by variations in refractive index; many have studied theoretically the mechanism responsible for the scattering (for example, *3*). Although clear-air echoes are often observed in the lower troposphere, clear-air radar layers from the tropopause also have been described (*4*); the tropopause marks the upper boundary of the troposphere and the lower limit of the stratosphere.

It is known that no unique relation exists between the intensity of clear-air radar echoes and the severity of turbulence (*4*). Instead, the intensity of the echoes depends on both the magnitude of the mean vertical gradient of refractive index and, in a complex manner, the severity of turbulence. The large vertical gradients of refractive index that frequently exist in the lower troposphere are detectable even when the turbulence within the region is much too little to affect aircraft. In the upper troposphere, however, the vertical gradient of refractive index is limited because of the almost negligible presence of water vapor in the atmosphere at high altitude. Under these circumstances it was inferred on theoretical grounds (*4*) that turbulence sufficiently intense to affect aircraft appeared to be necessary before the region of turbulence at the tropopause became detectable. This theory is supported by the results of simultaneous probing of CAT regions with narrow-beam microwave radars and by aircraft; this is a preliminary report of the results.

The experimental procedure with radar consisted primarily in taking slow-scan (0.1 deg/sec) photographs of the range-height indicators of the three radars. This type of scan provides a picture of the atmosphere in a vertical plane, from which one can determine the location and extent of any high-altitude clear-air radar layer; this type of layer is revealed only by the 10.7- or 71.5-cm radar (*4*). Airplanes were used as direct probes to determine whether turbulence was associated with the source of the radar echoes. Aircraft (*5*) made spiral ascents and descents, level flights, or porpoise runs (a sawtooth pattern about a mean height) in predetermined flight zones. About every 15 seconds the pilots reported their altitudes and qualitatively estimated the severity of turbulence encountered; their estimates were recorded on tape.

The results of four aircraft flights and observations by the 10.7-cm radar for regions above 6 km are summarized in Fig. 1. The heights of the sources of radar echo and their vertical extent were obtained from the range-height photographs. The altitudes of the radar layers and of the turbulences reported by aircraft are accurate within about 200 m. All high-altitude clear-air radar echoes are weak and are usually detected over a horizontal range of only 10 to 20 km. (The radar range of detectability is indicated qualitatively by the horizontal extent of the layers shown in Fig. 1.) Three of the radar layers occur near a height of 11.5 km, which corresponds to the level of the tropopause on such days. Moreover, the radar reflectivity of these layers is approximately 10^{-17} per centimeter, which is comparable to the values reported (*4*) for similar tropopause layers. Note, however, that turbulent clear-air layers also occur below the tropopause level.

The severity of CAT has been broken down into a relative scale based on the pilots' comments of zero, light, moderate, or severe turbulence, or combinations of these terms. The maximum observed turbulence for all flights, moderate to heavy, occurred on 20 March at a height of 11.5 km. The correspondence between the clear-air radar echoes and the location of the turbulence (Fig. 1) is obvious. The times and sources of the radar echoes and of aircraft reports of turbulence on 11 April and during the first flight of 12 April were nearly identical (within 5 minutes in time and 20 km in position horizontally). On 20 March and during the second flight of 12 April, however, radar echoes and turbulence were detected as much as 80 minutes apart, but still with good correspondence in height and horizontal location.

The high-altitude radar echoes were narrow (200 to 600 m), stratified, and somewhat patchy (horizontal dimensions of the order of 5 to 15 km); moreover the echoes were not especially persistent, often lasting less than a few tens of minutes. Also the turbulence was reported to be in relatively thin layers, the maximum thickness being about 1.5 km, centered near an altitude of 11 km during the first flight on 12 April. Although not determined quantitatively, the lateral extent of turbulence varied over narrow horizontal limits, usually less than 30 km. These dimensions are consistent with other aircraft probes of turbulence (*6*) and emphasize the patchiness that generally characterizes it; this patchiness is evident from both the radar and aircraft probes.

Note that on the second flight of 12 April some light turbulence encountered just above 9 km did not correspond to any radar echoes; similarly, light turbulence was apparently associated with some of the cloud boundaries. Also, on 13 April a flight encountered light-to-moderate turbulence in a region several kilometers beyond the maximum displayed range of the radars; thus the data for this day are not shown in Fig. 1.

The regions of clear-air echoes above 6 km that were simultaneously probed by aircraft were always found to be turbulent. This appears to be the first time that aircraft and microwave radars have simultaneously probed the same regions of the atmosphere and confirmed the close relation between radar echoes from high-altitude clear air and turbulence for aircraft in flight.

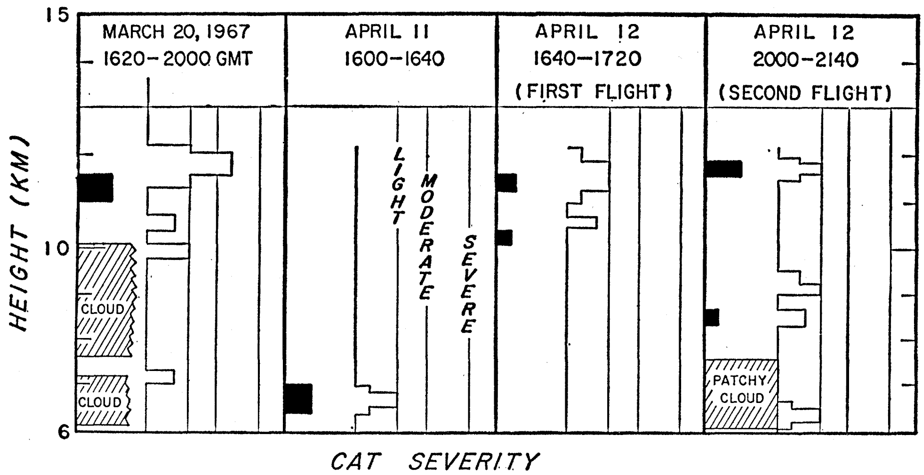

Fig. 1. Heights of radar echoes and reports of clear-air turbulence. Clear-air echoes are solid, cloud echoes are hatched, and aircraft encounters with CAT are open. The severity of turbulence is indicated by a relative scale deduced from the pilots' reports. The horizontal extent of the clear-air layers enables a crude estimate of the relative strength of the echo.

Zhupakhin (*7*) reported radar detection of the tropopause, but provided few details and obtained no confirmation of CAT by aircraft. Buehler and Lunden (*8*) investigated detection by radar of turbulence in the upper atmosphere, using several experimental techniques with very-high-frequency (VHF, 1.4- and 4-m wavelength) radars; their initial results with ground-based radars were so encouraging that they are proceeding with installation of a VHF radar in an aircraft; but the results of these experiments are still unknown.

The results in Fig. 1 suggest that ultrasensitive microwave radars can detect regions of CAT. A limitation, however, is the rather restricted range (less than 30 km) of the present ability to detect CAT. Doppler radar measurements of the echoing regions in clear air would also be valuable because the variance of the Doppler velocity spectra increases with increasing turbulence (*9*); it may be possible to determine the severity of CAT from the characteristics of the Doppler spectrum. Finally, light CAT is occasionally encountered (Fig. 1) that is not detected by radar, but radar did detect the one instance of moderate turbulence.

Additional experiments are clearly necessary before the practical utility of radar as a detector of CAT can be established. The program at Wallops Island during the winter of 1967–68 will include a period of intensive observations, with radar Doppler data combined with quantitative measurements of CAT by an instrumented aircraft.

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References and Notes

1. K. R. Hardy, D. Atlas, K. M. Glover, *J. Geophys. Res.* **71**, 1537 (1966).
2. I. Katz, in *Proc. Weather Radar Conf. 12th Boston* (Amer. Meteorol. Soc., 1966), p. 88.
3. For example, V. I. Tatarski, *Wave Propagation in a Turbulent Medium* (McGraw-Hill, New York, 1961).
4. D. Atlas, K. R. Hardy, K. M. Glover, I. Katz, T. G. Konrad, *Science* **153**, 1110 (1966); D. Atlas, K. R. Hardy, T. G. Konrad, in *Proc. Weather Radar Conf. 12th Boston* (Amer. Meteorol. Soc., 1966), p. 279.
5. From the 48th or 95th Fighter Interceptor Squadron, USAF; F-106's.
6. E. R. Reiter and A. Burns, *J. Atmos. Sci.* **23**, 206 (1966).
7. K. S. Zhupakhin, *Glavnaia Geofiz. Observ. Tr. 177* (1965), p. 129 [*Res. Transl. TR-629* (Air Force Cambridge Res. Labs., Bedford, Mass., 1966)].
8. W. E. Buehler and C. D. Lunden, *J. Appl. Meteorol.* **4**, 151 (1965); in *Proc. Nat. Air Meeting Clear Air Turbulence* (Inst. of Navigation–Soc. Automotive Engrs., 1966), p. 107.
9. D. Atlas, *Advances in Geophysics* (1964), vol. 10, p. 405.
10. Research aided by the director's fund of the Air Force Cambridge Research Laboratories and by NASA's Wallops Island Station. We thank the participating airmen, especially the pilots, Majors Wolford and Drinkwater and Captains Delk, Waddle, and Williams. We also thank the Wallops Island JAFNA radar-site personnel, especially the site manager, J. G. Howard, who assumed many additional coordinating responsibilities. Finally we thank Messrs. Donaldson, Glover, and Ottersten for helpful criticism throughout.

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