Wind Profilers for Support of Flight Operations

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Wind profilers are becoming an accepted component of meteorological observing systems. This paper discusses various types of wind profilers, illustrates their capabilities and the data they can provide to support flight operations, and discusses their limitations. In addition, the wind profiler has revived the radio-acoustic sounding system (RASS) technique for measuring temperatures. Preliminary RASS results are presented to demonstrate that wind profilers may also provide temperature measurements in the lowest part of the atmosphere; this capability substantially enhances their value for weather forecast services.

Introduction

THE wind profiler is a ground-based clear-air Doppler radar that can measure vertical profiles of horizontal and vertical wind in nearly all meteorological conditions. In just 10 years, wind profilers have moved from first research results to operational applications. Routine wind sounding in the troposphere by clear-air radar was first demonstrated in 1979.[1] In 1980, a program to develop the operational potential of wind profiling for meteorological observations was started. Preliminary results were presented to the aviation community in 1983.[2] A network of ultrahigh frequency (uhf) and very high frequency (vhf) wind profilers has operated continuously since 1983 in Colorado.[3] Data from this network are used by research meteorologists and operational forecasters. The success of this research network has led to the deployment of a 30-station wind-profiler network in the central U.S.; this network should be operational in 1990.[4] The wind-profiler technology has been transferred from government research laboratories to private industry, so the new network radars are being built commercially. Several U.S. companies are active in wind-profiler development. The groundwork is being laid for a European wind-profiler network. It is clear that the wind profiler will play an increasing role in operational and research meteorology, and this role will obviously affect aviation meteorology. Four types of wind profilers (described in the following in order of their status for operational deployment) have been developed for various meteorological measurements. All four have potential applications for support of flight operations. The term flight operations refers to any activity relating to flight where winds aloft are a concern.

The development of the wind profiler has led to a new look at the radio-acoustic sounding system (RASS) technique for measuring temperature. RASS provides temperature measurements through a straightforward extension to the wind-profiling radars, so the profiler becomes a more useful system for meteorological observations. Although RASS temperature profiles are made only in the lower part of the atmosphere, they can be used in conjunction with data from other instruments to provide temperature data throughout the troposphere.

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Tropospheric Wind Profiler

The tropospheric wind profiler, a clear-air radar that can measure wind profiles throughout the troposphere and into the lower stratosphere, is the most familiar type of profiler. It is now a commercial product, and it is intended to be used in networks to provide wind data for weather forecast services and fuel-efficient flight planning for commercial aviation. The original wind-profiler program objective was to develop profilers for these applications. The measurement objectives of this profiler are 1) nearly all-weather operation; 2) automated and continuous operation; 3) height coverage from near-surface to 17 km; 4) height resolution of 500 m; 5) time resolution of 1 h; and 6) accuracy of 1 m s^{-1} for orthogonal horizontal wind components.

There are a number of research radars throughout the world that can provide most of the desired features. Figure 1 shows an example of the time-continuous wind data that illustrate

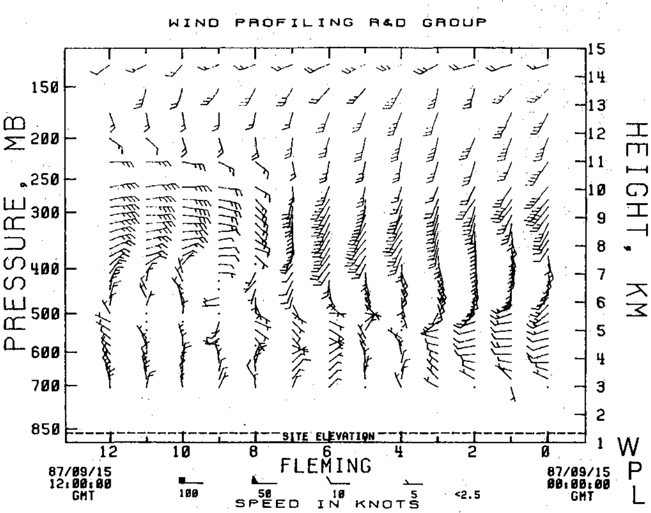

Fig. 1 Example of winds measured in real time with a 50 MHz wind profiler at Fleming, Colorado. Each hourly profile is an average of 12 measurements. Tropospheric wind profilers should provide similar data but with improved low-altitude coverage.

Table 1 Tropospheric wind profilers

Radar frequency	200–400 MHz (1.5–0.75 m wavelength)
Bandwidth	~1 MHz at −20 dB points
Antenna beamwidth	≤5 deg (one-way)
(Average power) (antenna aperture)	$\sim 5 \times 10^5$ W-m^2
Height coverage	Near surface to 17 km
Height resolution	~500 m
Time resolution	~1 h
Accuracy	~1 m s^{-1} for wind components
Cost	$350,000–450,000 (1987)
Status	Experimental radar network in operation since 1983 30-station network under construction

Fig. 2 Locations of 404.37-MHz tropospheric wind profilers for the wind-profiler network under construction. The network should be operational in 1990.

the profiler's potential importance for these meteorological observations. These data were acquired with a vhf (50 MHz) radar operating in northeastern Colorado. The display uses "flags and barbs" familiar to meteorologists to present a time-height cross section of the wind field over the radar. The radar measures a wind profile every 5 min; the display shows the hourly average of 12 observations. Most recent time is at the left to give a space-time interpretation to the display when the winds are from the west. The data shown in Fig. 1 are obtained routinely and automatically. There has been no filtering in time or height of the hourly data except the filtering provided by the resolution cell of the radar and the vertical sampling of the data at about 2/3 of the height resolution of the radar. Thus, there is some correlation between adjacent heights. This radar is not able to measure winds in the lowest 1.8 km above the surface because of the limited bandwidth allowed by frequency authorization, receiver recovery following the transmitted pulse, a physically large antenna that uses long cables to distribute the illumination, and ground clutter. A 4-yr archive of wind data from the Colorado network is available for research.

Table 1 summarizes the characteristics of radars suitable for tropospheric wind profiling. A major consideration for an operational network of wind profilers is the limited choice of operating frequency imposed by spectrum allocation. The operating frequency is limited at the high end to about 400 MHz (75-cm wavelength) because the clear-air scattering mechanism requires that scales of 1/2 the radar wavelength be in the inertial subrange of turbulence.[5] As altitude increases, the shorter scales of turbulence are damped by viscosity. Theoretical studies and experience with 10-cm-wavelength weather radars and wind profilers in the Colorado network (33- and 74-cm wavelength) indicate an upper frequency limit of about 400 MHz for this application. The radar frequency is limited at the low end by practical constraints on antenna size needed to form the radar beam. The physical antenna area for the 50-MHz radar that measured the winds shown in Fig. 1 was 2500 m^2; even so, the antenna beamwidth is larger than is desirable. The wind-profiler requirements would be readily met if the radar frequency is about 230 MHz.

The new 30-station network radars operate at 404.37 MHz. The availability of the 402–406 MHz band for "meteorological aids" was the major factor in choosing this frequency. The new network radars must adhere to strict emission limits to avoid interference with satellite communication systems. The prototype radar was installed at Platteville, Colorado in September 1988. Figure 2 shows the location of the profiler stations for this network. The central U.S. network is intended to determine whether wind profilers will improve weather prediction and whether a national wind-profiler network should be built. An extensive test of the quality and utility of the data for weather forecasting will be performed. The network will show the location and movement of synoptic flow patterns such as those associated with weather fronts and jet streams. The data will be available in real time to the aviation community for operational use. The profiler data present a challenge for numerical weather prediction because the continuous wind measurements and their time tendencies must be incorporated into forecast models before the real effect of profiler data can be assessed. However, from the reaction of local forecasters to the real-time data provided by the Colorado network (e.g., Fig. 1), it appears that the profiler data will find widespread use for forecasting and air-traffic routing. A current picture of the winds over the central U.S. should be useful to commercial carriers. The prototype profiler will be tested for several months at Platteville prior to starting production of the network radars in late 1989.

Lower Tropospheric Wind Profiler

Some wind-profiler applications require wind measurements only in the lower 4–6 km of the atmosphere. These applications often require single-station observations rather than data from a network as for synoptic weather observations. For example, flight operations at major airports could be assisted by continuous wind measurements to altitudes of interest to aircraft on approach, in landing patterns, or during takeoff. For these applications, the radar can have less sensitivity and a higher frequency than the profilers used for synoptic weather observations. Both time and height resolutions of the wind profiles must be better than those of the tropospheric profilers; profiles every 10 min with 150-m vertical resolution would be appropriate for many applications. These lower sensitivity (lower cost) profilers are also being developed by commercial firms. Table 2 lists the characteristics for this type of profiler. The radar sensitivity, determined primarily by antenna size

Table 2 Lower tropospheric wind profilers

Radar frequency	400–900 MHz (0.75–0.33 m wavelength)
Bandwidth	~2 MHz at −20 dB points
Antenna beamwidth	≤5 deg (one-way)
(Average power) (antenna aperture)	~10^3 W-m^2
Height coverage	Near surface to 6 km
Height resolution	~150 m
Time resolution	~10 min
Accuracy	~1 m s^{-1} for wind components
Cost	$120,000–150,000 (1987)
Status	Research systems at 405 and 915 MHz Commerical systems being developed

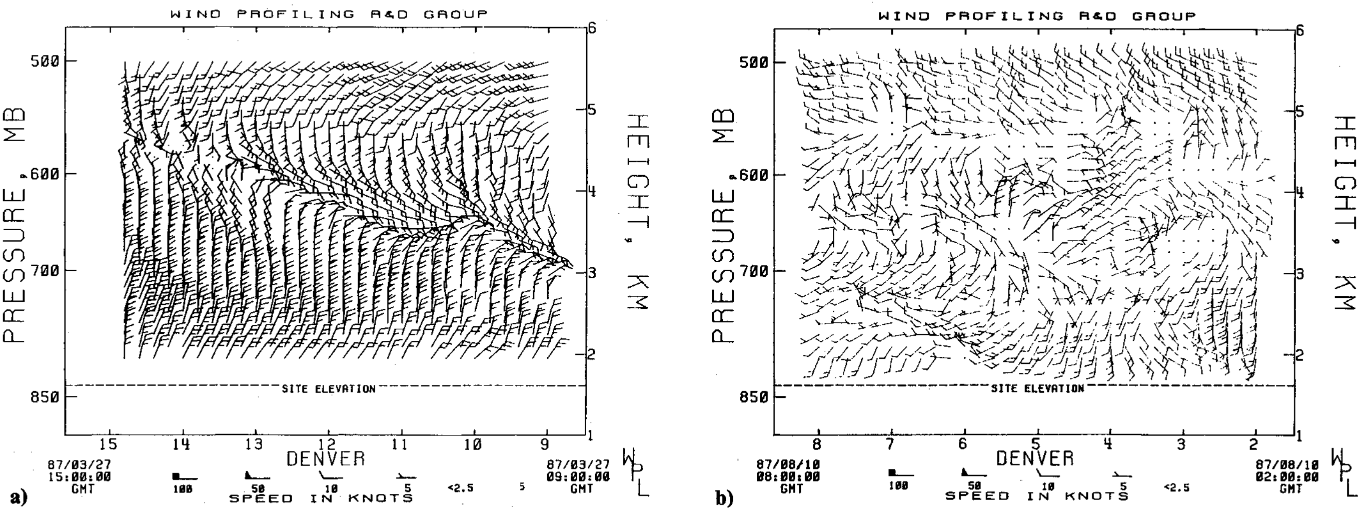

Fig. 3 Examples of winds measured with a 915-MHz lower tropospheric wind profiler at Denver's Stapleton Airport: a) shows a frontal passage; and b) light and variable summer winds that cannot be resolved with hourly averages. The wind profile is measured every minute; the display shows 12min. averages. The profiles represent raw data obtained in real time.

and average transmitted power, is about 26 dB less than the tropospheric profilers.

We have operated two profilers of this type; a 915-MHz radar at Denver's Stapleton Airport and a transportable 405-MHz radar operated in support of aerostat flight operations at Fort Huachuca, Arizona (aerostats are large tethered balloons that carry payloads to 10,000–15,000 ft altitude). These profilers measure winds with better time and space resolution than the tropospheric systems. They are able to do so because the clear-air radar reflectivity is generally much higher in the lower troposphere. The profiler at Stapleton Airport has operated as a lower tropospheric profiler since November 1986. From 1983–1986, it was operated in several modes that provided hourly averaged winds to near-tropopause altitudes. Research meteorologists working with these data often noted the lack of temporal and spatial continuity of the wind measurements at the lower altitudes, particularly in the summer months or in low-mean wind conditions. The radar is located about 30 km east of the Continental Divide, and the flow below about 4 km mean sea level (MSL) is frequently influenced by the terrain.

In November 1986, we changed the operation of this radar to measure winds every minute but to use only the best height resolution (150 m) to observe winds in the lower troposphere (to 5.5 km MSL). Figure 3 shows time-height cross sections of winds measured by this radar. The display shows the average of 12 profiles (5 profiles/h). The lowest height is about 300 m above the surface. During the winter months, the high-resolution profiles are used to study details of the interface flow during frontal passages (Fig. 3a), and to monitor the depth of upslope flow during winter storms. In cases such as these where the low-altitude flow is driven by large-scale air mass movements, hourly averaged winds retain the important features and show spatial and temporal continuity. For example, when the wind profiles shown in Fig. 3a are averaged for an hour, the frontal interface and general flow patterns are still evident. However, when low-altitude winds are light and variable, improved temporal resolution is needed to depict the flow patterns. Figure 3b shows an example of the variability of summer nighttime winds when improved time resolution must be used. Although the wind data from the Stapleton profiler are available in near real time and are used by local weather forecasters, they have not been used by the Stapleton Airport traffic controllers. They have been used by air traffic controllers at the Longmont, Colorado, Air Route Traffic Control Center.

The 405-MHz transportable wind profiler uses a 1.2-kW solid-state amplifier module as the transmitter and a 5.5-m-diam array of 76 Yagi elements as the antenna.[6] This relatively low-sensitivity radar has operated at Fort Huachuca, Arizona, since April 1988. It has been able to measure winds to about 6 km MSL with 150-m height resolution nearly all of the time, and most of the time it has measured winds to 8–9 km MSL with 450-m resolution. It has been so valuable to aerostat flight operations that aerostat sites may be equipped with a commercial version of this profiler. Figure 4 shows an example of horizontal winds that cause anxiety for the flight director. In addition, the profiler has demonstrated that it can measure vertical winds that cause severe problems for the aerostat tether.

Stratospheric–Tropospheric Wind Profilers

A third type of profiler, designed to measure winds with good range resolution throughout the troposphere and into the stratosphere, is being developed by a commercial firm to measure wind profiles to support rocket launches. Wind data are required to the altitude where stress on the launch vehicle due to winds is no longer a problem, typically 20 km. The effects of wind shear on launch vehicles for heavy payloads is a serious problem, both for safety and economy. These wind profilers must measure winds with height and time resolutions similar to those of the lower tropospheric profilers (150 m and 10 min) but to much higher altitudes. This requires a radar with much more sensitivity than the tropospheric systems have. Wind information is needed for programming the steering of the launch vehicle and to assess mechanical stress during ascent. The former does not require particularly good height resolution but the latter does. Table 3 lists characteristics for these "super" profilers. The antenna beamwidth of these systems must be narrower than that of lower-altitude profilers to maintain good height resolution at upper altitudes.

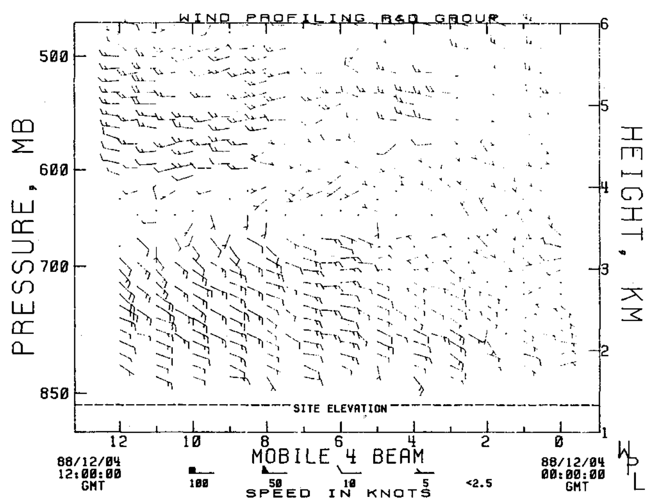

Fig. 4 Examples of winds measured with a 405-MHz lower tropospheric wind profiler at Fort Huachuca, Arizona. A large tethered balloon flies just below 4-km altitude, in the region of light winds at the interface between easterly and westerly flow. Winds are measured every 30 min, with height resolution of 150 and 300 m on alternating half hours.

Wind profilers (50 MHz) that will be able to measure winds with 150-m height resolution well into the stratosphere are expected to be operational in 1989. They will have 130-m-diam antennas with more than 10 kW average transmitted power. The antennas are built with collinear-coaxial elements and have three beam-pointing positions. Although wind profilers with this sensitivity have not yet been built, two vhf research systems with similar sensitivity have been operated. One of these radars, the MU radar,[7,8] is the most sophisticated radar of this type and is much more than a wind profiler. A second, sensitive vhf radar was operated at Poker Flat, Alaska, from 1979–1986.[9] Results from these radars indicate that the systems being built for this application will measure winds to above 18-km altitude with 150-m resolution. The data from these systems will initially be used to complement and supplement data provided by balloon soundings. The radars should be able to produce time–height wind profiles as in Fig. 3 except that the height coverage should be about 2–18 km above the surface. If the data prove to be reliable and accurate, the profiler could become a critical component for determining acceptable launch conditions. However, a single profiler will not provide an adequate picture of the winds for weather prediction, and a small array of profilers of the type used for synoptic weather observations has been proposed. A mini-network of this type would also provide useful data for landing spacecraft.

Boundary-Layer Profiler

A low-cost wind profiler for measuring winds in the atmospheric boundary layer has been developed.[10] This radar, originally built to measure winds near the surface to fill in the lowest altitudes not provided by vhf radars, will compete with acoustic wind-measurement techniques (SODAR) in a variety of applications. This radar has not yet been developed commercially, but the numerous potential applications make it attractive as a commercial product. The antenna is small enough to be mechanically steered, giving the radar advantages over fixed-beam SODAR. These systems will be used in research programs such as complex terrain studies or in operational applications for measuring low-level winds having time and space variability that cannot be observed with fixed-beam systems. The minimum altitude is about 100 m. This radar could be developed as part of an automated weather station for small airports, providing data such as those in Fig. 3 from about 100 m to 1.5–2 km above the surface with possible application to detecting dangerous wind-shear conditions. Table 4 lists radar characteristics for this type of radar.

Limitations of Wind Profilers

The wind profiler can measure the detailed wind profile above the radar with vertical resolution as fine as 150 m and temporal resolution as fine as a few minutes. The cautious ob-

Table 3 Stratospheric–tropospheric wind profilers for rocket launch support

Radar frequency	50–200 MHz (6–1.5 m wavelength)
Bandwidth	~2 MHz at −20 dB points
Antenna beamwidth	≤3 deg (one-way)
(Average power) (antenna aperture)	~10^8 W-m^2
Height coverage	Near surface to 20 km
Height resolution	~150 m
Time resolution	~10 min
Accuracy	~1 m s^{-1} for orthogonal wind components
Cost	$3-5 million (1987)
Status	Profilers for this application are under development by a commercial firm

Table 4 Boundary-layer profilers

Radar frequency	900–1500 MHz (0.33–0.2 m wavelength)
Bandwidth	~3 MHz at −20 dB points
Antenna beamwidth	≤5 deg (one-way)
(Average power) (antenna aperture)	~ 10^2W − m^2
Height coverage	~100 to 3 km
Height resolution	~100 m
Time resolution	~10 min
Accuracy	~1 m s^{-1} for orthogonal wind components
Cost	$40,000–60,000 (1987)
Status	Research system developed at 915 MHz

server will want to know the assumptions that are made, the validity of the assumptions in various weather conditions, if winds are measured during every time increment, the accuracy of the data, etc. Each of these topics has been (and will continue to be) examined as wind profilers are used in different situations. A brief summary of the major limitations of wind profilers follows.

Assumptions

Doppler radar wind profilers measure the vector wind at each height by measuring the radial velocity at several (usually three) beam-pointing positions. Thus, the wind components at each height are not measured in the same volume of air. For three-beam systems, the beam-pointing positions are usually in the zenith direction and off-zenith (about 15 deg) at orthogonal azimuths, so the oblique radar resolution volumes are displaced from the radar location by about $H/4$, where H is the height above the surface.

The basic assumption for the wind profiler is that the wind field (vertical and horizontal) is locally uniform and thus the winds are the same in all measurement locations. There are two reasons why this assumption is needed: 1) the vertical wind measured directly above the radar must be used to calculate the horizontal wind components measured with each oblique beam, and 2) the horizontal wind components are translated to the radar location when the vector wind is calculated. The latter calculation is not needed if the profiler is part of a network so that horizontal wind components can be analyzed at the grid points where the measurements are made. However, since the spacing between radars in any realistic network is much greater than the offset of the measurement cells, the horizontal wind measurements are usually assumed to apply at the radar location. Radial velocity measurements are averaged over time (rather than over space as with radars with scanning antennas) for periods of several minutes to an hour to make the local uniformity assumption valid for a wider variety of conditions.

It is apparent that there are conditions where local uniformity of winds cannot be assumed. For example, if the profiler is located in a mountain valley, wind measurements made at points separated by 1–3 km could differ because of terrain effects and time averaging would not reduce the difference. The most common situation where local uniformity cannot be assumed is in the convective storm. Here, the complex flowfields have time and space scales that cannot be measured with single Doppler radars; only the vertical motion can be measured and it cannot be assumed representative of vertical motion, even 1 km from the radar. Obviously there is a continuous range of scales of convective phenomena that will affect the profiler data because the local uniformity assumption is not entirely valid. Another meteorological situation that creates problems in terms of the local uniformity assumption is vertical motion resulting from gravity waves. Vertical motions that exceed about 1/4 m s^{-1} with temporal scales approaching the profiler averaging period (or longer) and have spatial scales comparable with (or shorter than) the separation of the measurement volume can cause errors in horizontal wind components that can exceed 1 m s^{-1}. Little is known about the occurrence of these types of waves, but preliminary analyses of measurements of vertical velocity obtained with wind profilers indicates that averaging periods of 1 h are usually, but not always, sufficient to reduce vertical velocities to less than 1/4 m s^{-1}.

In summary, the profiler is not expected to measure winds in strong convection such as that in the active portions of convective storms, and there can be errors in horizontal wind measurement caused by nonuniformity of vertical wind. Also, the profiler should not be sited where terrain effects produce complex wind fields.

Missing Data

It is frequently asked whether the profiler measures winds in every height resolution increment for every averaging period. We have already shown some limitations in minimum height coverage; the minimum height coverage of the new network radars will be 500 m above the surface, not as low as one would like for many applications. Profilers designed for boundary layer or lower tropospheric observations will have better coverage at low altitude, but 100 m is about as low as can be expected for pulse Doppler radars. Height resolution may not be good enough for some applications. The tropospheric wind profilers may not have enough sensitivity to measure winds in the upper troposphere for all weather conditions. Clear-air radar reflectivity is highly variable at all heights; just below tropopause it is often very low. There can be data missing at some heights for some time increments, depending on the sensitivity of the radar. A typical profiler might be designed with enough sensitivity to measure hourly averaged winds at all altitudes below 12 km, say 98% of the time, and from 12–16 km, 90% of the time. Total elimination of these missing data would require an increase in radar sensitivity, and therefore in cost, that could not be justified for most weather-observation applications.

Accuracy

Numerous comparisons of wind-profiler data with winds measured by balloon techniques have been made, including one rather complete study.[11] These comparisons give results similar to those obtained when wind data from a single balloon are measured by two different trackers, about a 3-m s^{-1} rms difference in wind speed.[12] Comparisons of balloon and profiler data typically have rms differences between wind components of 3 m s^{-1}. If one examines wind profiles as illustrated in Figs. 1, 3, and 4, one should not be surprised to find these differences because the balloon measurements are never made directly above the radar. To date, balloon–profiler comparisons have been "blind"; that is, no attempt has been made to compare data when the winds measured by the profiler were not changing in time when good agreement should occur. Such comparisons are now being made by studying 5 yr of wind-profiler data obtained with the Stapleton Airport profiler which is collocated with the National Weather Service (NWS) balloon launch facility.

The precision of wind-profiler data obtained with a 405-MHz wind profiler has been shown to be better than 1 m s^{-1} at low altitudes where signal-to-noise ratio (SNR) is high, and it degrades to about 1.2 m s^{-1} at the lowest SNR.[13] The accuracy was found to be limited by meteorological variability in the winds causing them to be slightly different in the spatially separated volumes probed by the wind-profiler antenna. In precipitation, even though the SNR may be higher (because uhf radars observe precipitation scattering), the precision is degraded by about a factor of 2 because of increased wind variability and because of nonuniform precipitation, which appears as noise to the mean wind measurement.[14] An additional accuracy degradation can be caused by nonuniform radar reflectivity within the radar resolution volume.[15] If reflectivity is nonuniform, then the radial velocity measured by the radar can be biased because the effective radar range or elevation angle of the antenna can be different from the actual values. These effects are minimized with narrow beam antennas and good height resolution.

Temperature Measurements with Wind-Profiler Radars

The development of the wind profiler has led to a recent reexamination of an old technique for measuring temperature profiles. RASS was first investigated in the early 1960's, but it has received almost no attention in the U.S. since the mid-1970's. RASS is a method for measuring the vertical profile of the speed of sound with a Doppler radar; the virtual temperature is found directly from the speed of sound. Although not pursued in the U.S., the RASS technique was developed in Europe[16] as a meteorological probe for temperature profiling the lowest 1 km of the atmosphere. The addition of temperature measurements to the wind profiler adds an important element for weather forecasting. The temperature data are measured with the same temporal and spatial resolution (in the lowest few kilometers of the atmosphere) as the winds.

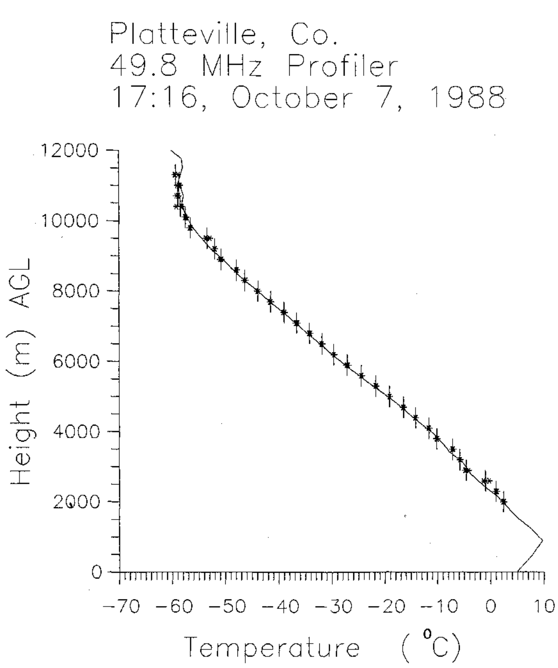

Fig. 5 Temperature profile measured by RASS (asterisks) and a radiosonde (solid line). The lower heights are not measured by RASS with this radar because of recovery time following the transmitted pulse. Typical upper-altitude coverage with RASS is 6–8 km, but on this day atmospheric conditions allowed measurement to the tropopause.

It is widely believed that RASS is quite limited in altitude because of acoustic attenuation and the effects of winds and turbulence on the radar signal backscattered by the acoustic waves. That view has been somewhat altered by recent results obtained with wind-profiler radars. Temperature profiles to 20-km altitude were measured with a vhf radar[17] having a steerable antenna that could point the electromagnetic beam in the proper direction to compensate for the effects of wind on the acoustic waves. Using fixed-beam wind-profiler radars and fixed acoustic sources, May et al.[18] have shown that temperature profiling in the lowest 3 km of the troposphere (and perhaps to higher altitudes) will be achievable with the new wind-profiler network radars. In a recent experiment with a 50-MHz wind profiler, a RASS temperature profile was measured to the tropopause (Fig. 5); atmospheric conditions had to be exceptionally favorable to obtain these results. Typical altitude coverage is about 6–7 km above the surface with this 50-MHz wind profiler. The shorter wavelength radars used in the wind-profiler network will be more limited in height coverage. Nonetheless, the RASS data are expected to be a very valuable addition to the wind profiler because they can be used to aid in measuring the complete temperature profile when they are combined with other measurements.

The RASS data combined with data from satellite-borne microwave radiometers hold particular promise for tropospheric temperature profiling because the RASS data complement data from the satellite radiometer. The weighting functions of the satellite radiometer have best resolution in the middle and upper troposphere and poor resolution near the surface where high resolution RASS measurements would be available. Various aspects of the RASS technique are now under investigation.

Concluding Remarks

In less than a decade, the idea of continuous measurement of tropospheric winds with Doppler radar has advanced from first research results to operational radars. It is clear that wind profilers will be in widespread use in the next decade; they will bring to the flight controller a picture of the present and past winds and perhaps the temperature in the lower troposphere. It is too soon to say whether forecasters will be able to use these data to improve weather prediction, but perhaps a future update of the wind-profiler capability for support of aviation will show the profiler as part of an improved observing *and* forecasting system. By the mid-1990's, we will know the value of real-time wind profiles for support of flight operations.

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