Abstract

During the week 29 October–4 November 1988, a Ground-based Atmospheric Profiling Experiment (GAPEX) was conducted at Denver Stapleton International Airport. The objective of GAPEX was to acquire and analyze atmospheric-temperature and moisture-profile data from state-of-the-art remote sensors. The sensors included a six-spectral-channel, passive Microwave Profiler (MWP), a passive, infrared High-Resolution Interferometer Sounder (HIS) that provides more than 1500 spectral channels, and an active Radio Acoustic Sounding System (RASS). A Cross-Chain Loran Atmospheric Sounding System (CLASS) was used to provide research-quality in situ thermodynamic observations to verify the accuracy and resolution characteristics of each of the three remote sensors. The first results of the project are presented here to inform the meteorological community of the progress achieved during the GAPEX field phase. These results also serve to demonstrate the excellent prospects for an accurate, continuous thermodynamic profiling system to complement NOAA’s forthcoming operational wind profiler.

1. Introduction

This paper presents preliminary results from the field phase of the Ground-based Atmospheric Profiling Experiment (GAPEX), conducted 28 October–4 November 1988. The experiment consisted of observations from three remote sensing systems: 1) a Microwave Profiler (MWP) consisting of six spectral channels for sensing lower tropospheric temperature profiles, total water-vapor concentration, and total liquid-water content; 2) a High-Resolution Interferometer Sounder (HIS), which measures the infrared spectrum (4–18 μm) with very high spectral resolution (λ/Δλ = 3000), for profiling temperature and water vapor throughout the lower troposphere, as well as for providing total concentration measurements of ozone, methane, carbon monoxide, and the chlorofluorocarbons; and 3) a Radio Acoustic Sounding System (RASS) which, through Doppler-radar measurement of the speed of acoustic waves, provides an accurate measure of the temperature structure of the lower troposphere. A Cross-Chain Loran Atmospheric Sounding System (CLASS) provided in situ wind, temperature, and water-vapor measurements for evaluating the results of the three remote sensing systems. Because of the different physical principles governing each remote sensor, their capabilities differ with respect to each atmospheric variable (temperature or humidity) being retrieved, altitude coverage, and the effects of cloud, aerosol, and turbulence. After investigating the differences between the profiling capabilities and limitations of each system, a primary objective of the project is to develop methods of processing these data so as to demonstrate the profiling accuracies achievable by ground-based remote sensing. The ultimate goal is to demonstrate how the three systems can be used in concert to provide accurate, continuous thermodynamic measurements of the lower atmosphere as a component of a network of profilers. A complete system to sound the entire atmosphere would require integration of data from both ground-based and satellite sensors.

2. The remote sensors

a. Microwave Profiler

The MWP has been operating continuously and unattended at Stapleton International Airport since 1981. The principal products of the system are low vertical-resolution temperature profiles, and integrated amounts of water vapor and cloud liquid. Following Hogg et al. (1983), we summarize the
essential features of the instrument.

The MWP measures brightness temperatures at six frequencies (20.6, 31.65, 52.85, 53.85, 55.45, and 58.8 GHz). The lower two channels are sensitive to water vapor and cloud liquid; the upper four, operating in the 60 GHz O₂ molecular band, are sensitive to temperature. All six channels have the same beam width of 2.5° and simultaneously measure zenith emission from the same solid angle. The zenith radiation is reflected from a flat reflector through a transparent window onto offset parabolic antennas. The electronics and parabolic antennas are housed in a trailer whose temperature is controlled to within ±5°C; over a year's time, the internal temperatures of the instrument vary by less than ±1°C. Internal calibration of the instrument is achieved by sequentially switching between the antenna and two reference black-bodies. External calibration procedures require "tipping curves" and/or radiative transfer calculations based on radiosonde data. Calibration factors require infrequent updating, perhaps once a month.

Temperature, water vapor, and cloud liquid are derived every 2 min from the MWP, using a profile-retrieval technique known as "linear statistical inversion" (Westwater and Strand 1968). The statistical accuracies of the derived parameters have been evaluated by comparison with National Weather Service (NWS) radiosonde data (Westwater et al. 1985). The accuracies of derived precipitable water vapor and geopotential heights to 500 mb are comparable with the accuracies of radiosondes. Above the 1 km AGL, the vertical resolution of temperature profiles degrades rapidly, with the consequence that elevated inversions are not resolved.

The sensitivity of the MWP is such that rapidly changing dynamic features, such as frontal movements, are easily observed. In addition, spectral analyses of data have frequently shown evidence of gravity waves that were confirmed by independent observations (Ciotti et al. 1987; Canavero et al. 1989). Figure 1a, for example, shows a plot of the total precipitable water vapor observed by the MWP during the GAPEX. Shown for comparison are 3-h interval CLASS-sondes, 12-h interval National Weather Service (NWS) radiosondes, and estimates obtained by vertical integration of the HIS water-vapor profiles. The MWP does an excellent job of observing the time variation of total precipitable water, and the agreement of the MWP with the CLASS is generally better than the agreement between the NWS radiosonde and CLASS. The root mean square (rms) difference between MWP and CLASS total precipitable water-vapor values is only 0.04 cm. For comparison, the rms difference between HIS and CLASS precipitable water-vapor values is 0.06 cm, while the rms difference between the standard NWS radiosonde and CLASS precipitable water values is 0.07 cm. The MWP total-column water-vapor estimates are expected to be more accurate than the infrared HIS values due to the lower sensitivity of microwave radiation to clouds and aerosols.

Because of its proven reliability, its near all-weather capabilities, and its high sensitivity to small changes in measured radiance, the MWP continues to provide routine and useful meteorological observations. Unfortunately, the microwave technology is relatively expensive to implement on a large scale. Its ultimate use depends on the degree to which its data enhance the results achieved with other, less expensive systems, such as HIS and RASS. For example, HIS and MWP might conceivably yield high-quality soundings during both clear and cloudy conditions; a MWP-RASS combination has already shown an improvement over either system alone (Schroeder 1989).

b. High-Resolution Interferometer Sounder

The HIS instrument used in GAPEX is a Michelson interferometer developed primarily as an aircraft prototype of a new-generation satellite sounder (Smith et al., 1989; Revercomb et al. 1988). It operates in the infrared region between 600 and 2600 wavenumbers.

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1 Approximately $450 000 for a six-channel system; ~$150 000 for a two-channel system; and a dual-channel system might be mass produced for about $50 000.
(i.e., 16.8–3.8 μm) using three detectors to divide the spectrum into three bands: band 1 (600–1080 cm⁻¹), band 2 (1080–1850 cm⁻¹), and band 3 (2000–2600 cm⁻¹). The spectral resolution of the raw data is about 3000:1. The data are processed by Fourier transformation of a truncated and apodized interferogram yielding a spectral resolution of about 0.5, 1.5, and 1.5 cm⁻¹ for bands 1, 2, and 3, respectively. When the interferometer was operated in the upward-looking mode at Denver, complete spectra were achieved every 4 sec. Two blackbodies, an Eppley cavity heated to 300 K and a bath of liquid nitrogen at 77 K, were used to calibrate the measurements once per minute. The sky at local zenith and the blackbody references were viewed using a scene-switching mirror. For atmospheric profiling purposes, the calibrated spectra, produced every 4 sec, are averaged over 5-min intervals with the mean and standard deviation spectra being output for use in sounding and trace-gas concentration retrievals.

Two examples of radiance spectra observed with HIS are shown in Figure 2 along with spectra calculated using a regression atmospheric transmission model based on flight acceleration safety cutoff system Fast Atmospheric Signature Code (FASCODE) (Clough et al. 1988) and a CLASS sounding of temperature and water vapor. There is extremely good agreement between the spectral features shown in the observed and the calculated spectra, the minor exception being in the “window” region between 800 and 1000 cm⁻¹ (panel 1) due to emission by Freon 11 and 12 which was not included in the FASCODE calculation. The mean difference and standard deviation of all the observed and calculated spectral radiances achieved during the entire GAPEX period is shown in Figure 3. Because the observed spectra are believed to be accurate to better than 0.5%, the differences shown are due primarily to errors in the FASCODE spectroscopy with second-order differences due to time and space variability in atmospheric temperature and water vapor.

One attractive feature of the Michelson interferometer technology is its simplicity and associated low cost. The basic interferometer instrument capable of performing the ground-based atmospheric profiling task is commercially available (from Bomem, Inc.) at less than $30 000. We believe that the complete system, including an automated calibration facility, and a data-processing-and-dissemination system could be mass produced for less than $50 000. Thus, the HIS technology is an attractive candidate for worldwide implementation as a ground-based meteorological profiler and trace-gas concentration monitor.

The linear simultaneous statistical inversion method (Smith et al. 1989) was used to retrieve atmospheric temperature and dew-point temperature profiles from the HIS spectra. The covariance matrices of temperature and dew point utilized in this solution were obtained from the same 10-yr climatological sample of radiosonde observations at Denver (Westwater et al. 1985) used for the MWP retrievals. Figure 1b shows a plot of the 500-mb geopotential height derived from the HIS temperature and water-vapor profile retrievals as compared to the CLASS, standard NWS radiosonde observations, and the MWP. The rms difference between the HIS and the CLASS is only 12 m. (For comparison, the MWP comparisons with CLASS provide an rms difference of 17 m.) The 17-meter rms differences were slightly larger than the value of 12.5-m rms obtained over a year’s operation (Westwater et al. 1984). Geopotential height profiles derived from HIS are expected to be more accurate than those from the MWP because of the much larger number of temperature and water-vapor-sensitive sensor channels.
The experiments reported here make use of the 915-MHz Denver profiler, which unfortunately has the poorest height coverage of any of the WPL wind profilers (May et al. 1988). The other profilers operate at lower frequencies (the acoustic absorption by the air increases rapidly with frequency and this is one
of the main limiting factors concerning height coverage). Furthermore, the conditions encountered during GAPEX were cool and dry, again where the acoustic absorption has a strong maximum.

The Denver profiler (Hogg et al. 1983; Strauch et al. 1984) operates at a frequency of 915 MHz ($\lambda = 0.327$ m) and consists of an offset paraboloid antenna with separate feeds for different beam directions (Zenith, and 15° N and E from zenith). Only the vertical beam has been used for RASS. The radar pulse-length is 1 μsec giving a range resolution 150 m. The lowest range sampled is 200 m above the ground. For RASS, 16 range gates were sampled, but a detectable signal was not received in all of them. During the latter half of GAPEX, when RASS was operating well, the height coverage was up to 1.54 ± 0.26 km (~11 gates). For RASS, a frequency offset was introduced in the local oscillator so that the receiver sampled an interval of ±50.56 m s$^{-1}$, about a frequency shift corresponding to a velocity of 300.38 m s$^{-1}$, allowing the speed of sound to be measured. The present RASS measurements do not correct for the effect of vertical velocities on the speed-of-sound measurements. However, wind profiles can directly measure the vertical wind. A system is being designed to eliminate the need for the frequency offset in the receiver and to allow corrections for the vertical component of the wind, by measuring the clear-air component simultaneously with RASS.

Four acoustic sources were placed around the radar antenna at approximately 90° intervals in azimuth. The use of multiple sources decreases the effect of the horizontal wind that displaces the acoustic wavefronts. Each source consisted of a high-power transducer mounted above a 1.1-m diameter paraboloid dish. This gives a beamwidth of about 8°. The total transmitted acoustic power was about 10 W for each source. Triangular frequency modulation was employed so that, for all the sampled heights, there was a Bragg match between the acoustic and radar wavelengths at some height within the radar-pulse volume.

Figure 4 shows a scatter plot of the RASS temperature observations at 815 mb vs CLASS, radiosonde, HIS, and MW data. The rms difference between the RASS and CLASS is 0.5°C. For comparison, the rms difference between the HIS and MWP 815-mb level temperature from the CLASS are 0.8°C and 1.0°C, respectively. For level-temperature estimates, the RASS is expected to be superior to the HIS or MWP since its measurement is more directly related to the level value. (RASS possesses 150-m resolution, unlike the HIS and MWP, whose spectral radiances represent broad-layer integrals.)

We note that NOAA is currently procuring a network of 30 wind profilers for the central United States. A RASS capability could be added to the radars, at relatively small additional cost, to greatly enhance the impact of the network.

d. Cross-Chain LORAN Atmospheric Sounding System

The CLASS tracks a conventional radiosonde that receives and retransmits LORAN signals to a ground-based receiver and computer system. The ground system is housed in a small trailer, using a conventional aircraft LORAN navigator to unscramble the LORAN signals and transfer the time-of-arrival data to a personal computer. Winds are determined by the change in position of the 200-g balloon; independent wind estimates are obtained every 30 sec with intermediate winds estimated at 10-sec intervals. State variables (temperature, pressure, and humidity) are received approximately every 3 sec.

The self-contained, towable trailer (3.6 × 2.4 × 2.1 m) contains balloon inflation and launch apparatus, an electronics rack for receiving the sonde radio frequency (RF) signals, and a desktop computer for data acquisition, processing, and system control. A nearby tower supports the antennas, preamplifier, and surface weather station. An uninterruptible power supply and gasoline-powered generator permit continuous operation should commercial ac power fail.

A 200-g balloon is inflated within a cloth bag attached to a 1.5-m diameter ring in the ceiling of the trailer. At launch, a hatch cover on the trailer roof is moved to expose the balloon. The bottom of the balloon bag is open and permits attachment of the sonde-line let-down device to the neck of the balloon. At launch, the trailer-mounted antenna disconnects from the sonde and the sonde antenna unwinds from the let-down device.

The 400-MHz RF signal from the Vaisala RS-80L radiosonde is received by the antenna on the tower assembly and fed coaxially to a sensitive, wide-bandwidth (500-kHz) FM receiver. The receiver is tunable across the 400-MHz meteorological band and has indicators of frequency and signal strength, and a speaker for audio output. Signal outputs are provided for the 7–10-kHz thermodynamic frequencies and the 100-kHz LORAN-C frequencies.

The thermodynamic frequencies are processed by a Vaisala PP-11 PTU processor into units of pressure, temperature, and humidity. These values are displayed on the PP-11 front panel and sent to an RS-232 serial data port for computer access. The PP-11 has a paper-tape reader for inputting radiosonde sensor coefficients and a keypad for entering sonde baseline data.

The LORAN-C frequencies are processed by ele-
ments of an aircraft LORAN-C navigator, specially modified for use in CLASS. The ANI-7000 navigator automatically identifies, acquires, and tracks up to eight LORAN stations simultaneously. The stations can be from any mix of LORAN chains, hence the "cross-chain" capability. The CLASS computer obtains the LORAN data through an RS-232 port.

The hardware control, data acquisition, data processing, and communications activities are handled by a Hewlett-Packard (HP) series 200/300 computer. The software was written with HP's advanced BASIC language. Data are stored on a floppy disc for later use. Data communications are provided by a Hayes 1200-baud Smartmodem.

The CLASS software system consists of a main menu with five major segments driven by soft-key functions. These are hardware control, real-time data computation, flight-data analysis, miscellaneous functions, and communication. Real-time CLASS data consist of 10-s smoothed-wind data, PTU data, and corresponding quality data. PTU data are smoothed over 20 s, using a least-squares solution. Wind data are computed from time-of-arrival of three or more LORAN-C station signals. These data are smoothed over 30 s using a least-squares fit.

Any number of derived quantities are available. Standard outputs include altitude and dew point, the user specifying other derived parameters. Printouts are available through soft-key access of 10-s data, pressure-level data for any desired pressure increment, and raw data. Quality flags are assigned to the pressure, temperature, humidity, and wind data indicating the probable error in the measurement. In-flight and post-flight plots are available for all parameters.

3. Example comparison

Observations with the CLASS, MWP, HIS, and RASS were conducted intermittently from 28 October to 4 November 1988. On 1 November, all four sounding systems were operated simultaneously at 3-h intervals, the MWP and HIS data being recorded continuously throughout the 24-h period. Figure 5 illustrates temperature profiles observed by each sensor within the 850–650-mb layer at 3-h intervals; note that mean surface pressure at Denver is about 850 mb. A close inspection of these comparisons reveals:

1) All three remote sensing systems appear able to sense temperature to within 1°C of the CLASS verification data, the largest disagreements being near the surface inversion level (820 mb) and near the top of these plots (i.e., 650 mb).

2) Over the limited vertical domain of its observation, the RASS provides the highest vertical resolution. Its bias relative to the CLASS is apparently due to the influence of vertical motion on the measured acoustic wave speed which was not corrected in the transformation of the acoustic velocity to atmospheric temperature. The vertical winds measured before and after the RASS observations were well correlated with the bias, but wind fluctuations preclude attempts at a correction here.

3) The MWP discrepancies with CLASS tend to increase more rapidly with altitude than do HIS discrepancies. This was expected because of the much larger number of spectral channels possessed by HIS as compared to the MWP.

Figure 6 shows the rms difference between the CLASS verification and the MWP, HIS, and RASS tem-
Fig. 7. 3-h time tendency of dew-point temperature profiles observed by the HIS and CLASS sounding systems on 1 November 1988.
FIG. 6. The rms difference between the three remote-sensing systems from the CLASS observations. The standard deviation of the CLASS temperature profiles about its mean for the period of study is also shown. Dew point temperature is referred to as Td.

4. Summary

The initial results of the GAPEX demonstrate that each of the remote sensors operated in a highly successful fashion. The next steps that need to be taken in the data analysis are

1) To investigate how the temperature and water-vapor profile product might be improved through various combinations of the remote-sensor signals (e.g., water-vapor profiles might be improved using the MWP total precipitable water and the RASS temperature profile as a constraint on the HIS retrieval).

2) To investigate the effect of clouds and aerosols on the profile retrievals from the infrared spectral-radiance data, and to develop an algorithm for accounting for cloud effects in the profile-retrieval process.

3) To develop a profile-retrieval methodology that provides optimal temperature and water-vapor retrievals, regardless of cloud conditions, from the combination of HIS, MWP, and RASS measurements. The periodic (every 6–12 h) use of CLASS-sondes and the incorporation of numerical forecast profiles to improve the absolute accuracy of the product also need to be investigated.

4) To investigate the combination of observations from surface-based sensors with satellite observations to optimize the accuracy of remotely sensed thermodynamic profiles throughout the entire atmosphere.

Finally, these initial results are from a very small sample of observations achieved over a relatively short time period. The experiment needs to be conducted again over a much longer time period to investigate the dependence of the accuracy of the various techniques on different types of weather and seasonal variations.

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References

Bonino, G., G. Elisei, A. Marzorati and P. Trivero. 1986. Results on planetary boundary layer sounding by automatic RASS. At-


