# A New Aerological Sonde for Dense Meteorological Soundings

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ABSTRACT

A new recoverable aerological sonde has been developed for studying mesoscale atmospheric processes. It allows for precise temperature, humidity, pressure, and wind measurements with (i) high spatial resolution (e.g., up to 100 m) as a parachute dropsonde version and (ii) high temporal resolution as balloon sonde version. The sonde comprises sensor elements of a commercial radiosonde, a 12-channel GPS receiver, a mobile telephone, a microcontroller as a central processing unit, a 4-Mbyte flash memory, a power pack, and a UHF transmitter. Data are stored internally and no data telemetry is used except for GPS data of the landing location, which are transmitted via mobile telephone for sonde recovery. Accurate offline differential GPS (DGPS) wind solutions are obtained by simultaneous GPS reception of a stationary receiver. Optionally, DGPS-based wind data may be obtained by reception of GPS corrections transmitted via VHF or satellite. After removal of selective availability from GPS signals in May 2000, winds based on GPS stand-alone solutions only are found to be of similar quality as DGPS winds. Arbitrarily, many sondes (typically 30 sondes) can be operated simultaneously and no ground-based or aircraft-based station is required for this purpose. Extensive tests of the dropsonde version have proved the reliability of the entire system and the acquired data. Due to the high probability of recovery, the possibility of multiple use without calibration or major refurbishment, and the optional extension by other sensors, the system is considered an alternative to standard sondes applied for research purposes.

## 1. Introduction

Standard radiosondes from different manufacturers are operated by National Weather Services for global monitoring of the state of the atmosphere. About 12 different types of radiosondes are used worldwide, 6 of which make up for 90% of all ascents (Richner et al. 1996). Data are regularly transmitted via the Global Telecommunication System (GTS) and used by assimilation schemes within numerical prediction models. Comparisons made by the World Meteorological Organization (WMO) revealed a high degree of reliability of most radiosonde systems (Oakley 1998). For certain scientific purposes, standard radiosondes may have shortcomings, such as limitations in operating several aerological sondes flexibly and simultaneously in the same region. Such restrictions result from the limited bandwidth of the frequency band used for telemetry and from the normal requirement of one ground-based receiving station for each sonde. Radiosondes are usually considered one-way products, though sondes that have been found by chance may be used again frequently.

For research purposes, alternative solutions have been realized, such as a tethersonde system for up to six sondes [Atmospheric Instrumentation Research, Inc., (AIR) Boulder, Colorado], whose data are transmitted to a single ground station. In an arctic research program (Hartmann et al. 1996), densely spaced drop soundings were made by using sondes with different carrier frequencies. Multiple radiosondes to be launched simultaneously have been developed and launched by Corner

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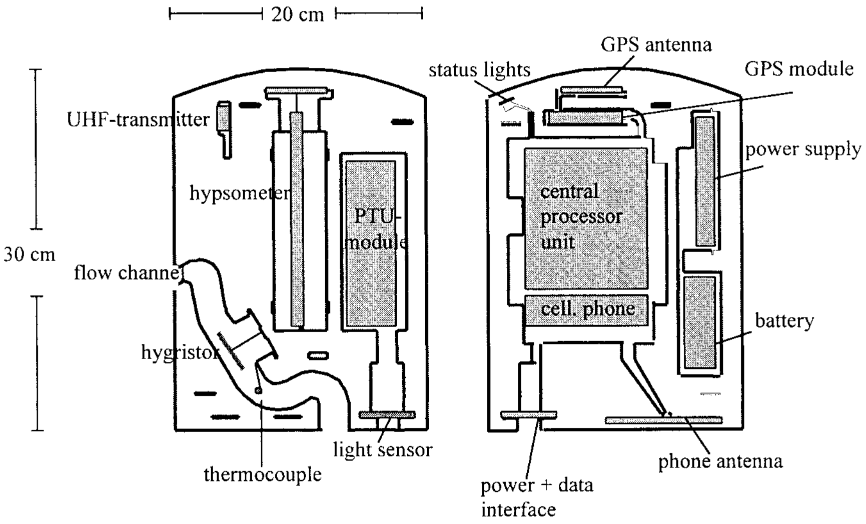


FIG. 1. Schematic overview of the dropsonde and its main components.

et al. (1999). Their sondes are tracked by a photographic camera system that restricts wind estimates to the range of optical visibility. Cooperation between the National Center for Atmospheric Research, Deutsches Zentrum für Luft- und Raumfahrt, and Vaisala Co. (Cole 1997) yielded a new dropsonde and a four-sonde telemetry system for release from an aircraft. The telemetry system is designed for a horizontal spacing of 100 km between drops from a jet aircraft flying at tropopause level. A similar system is available for low-flying aircraft and unmanned vehicles (Ikonen 1997). Most radiosondes nowadays use GPS wind finding (Call 1997; Saarnimo 1997).

The technical solution described here pursues a rather different approach. The presently available sondes of the new type are dropped from an aircraft with a parachute, whereby a typical drop interval of 2 s can be achieved. Measured data are no longer transmitted via radio link, but rather stored internally. The sondes are recovered after operation for data recovery and repeated use. This compensates significantly for the higher costs of the sonde and optional equipment, which are not lost. The main advantages of the new system are (i) the possibility of achieving a high spatial resolution (up to 100 m) and (ii) the simultaneous use of many sondes (e.g., 30 sondes). Both features are of great importance to the study of mesoscale meteorological phenomena. The development became possible due to the rapid progress made in recent years in the fields of GPS and mobile communication technology.

## 2. Technical description

The sonde is designed to (i) obtain aerological data with the same accuracy as standard radiosondes, (ii) be extendible for measuring three additional parameters, (iii) be recoverable and repeatedly usable, (iv) operate independently of any radiosondes of the same or other type in its vicinity, and (v) be as cost-effective as other available radiosonde systems. This is achieved by a novel combination of commercially available sensor and electronic components (Fig. 1). The sonde mainly consists of a meteorological PTU-sensor module (Meteolabor SRS 400-PTU), a Navigation Signal Timing and Ranging (NAVSTAR) GPS receiver (Garmin GPS 25 LVS), a central processor unit (Phytec 8051) with flash EPROMs for program and data storage, a Global Standard for Mobile Communication (GSM) modem (Siemens M20), and a UHF transmitter (HM Funktechnik 70 TX-M1). All parts are mounted in a hard-foam housing of dimensions 20 cm × 30 cm × 15 cm. The weight of the sonde is about 950 g.

### *a. Meteorological sensors*

The meteorological sensors are from the SRS 400 radiosonde that is in operational use by the Swiss Meteorological Agency and the Swiss Armed Forces (Ruppert 1999; Richner 1999). Temperatures are measured by 63-$\mu$m copper/50-$\mu$m constantan thermocouples of different dimensions for stability reasons. A very stable copper temperature sensor in an aluminum block is used for reference. The pressure sensor, being also used for height determination, is a hypsometer (Ruppert 1991) filled with 1 $cm^3$ (milliliter) of distilled water. The hypsometer has been developed by the Swiss Meteorological Institute, the Meteolabor Company, and individual scientists (Richner et al. 1996). To achieve the necessary accuracy over the complete range of temperatures, pressures, and operational conditions of a standard radiosonde, a very accurate temperature measurement and a specific controlling circuit for heating the water were required. Humidity is normally measured by a carbon–cellulose film hygristor (VIZ Accu-Lok). To obtain very

TABLE 1. Sensor specification of the SRS 400, the dewpoint mirror snow white, and the GPS wind-finding, the latter being estimated from GPS–DGPS position comparisons (Biegert and Wende 2000).

| Parameter | Temperature | Humidity | Humidity | Pressure | Wind |
|---|---|---|---|---|---|
| Type | Thermocouple | VIZ Accu-Lok | Dewpoint mirror snow white | Hypsometer | GPS–DPGS |
| Range | +50° to −100°C | 5%–100% | +50° to − 100°C | 1100–5 hPa | |
| Accuracy | <0.1°C | 5% | 0.3°C | 0.2% | 0.5 m $s^{-1}$<br>0.3 m $s^{-1}$ |
| Resolution | 0.01°C | 0.01% | 0.01°C | 0.02% | 0.1 m $s^{-1}$ |

accurate humidity values, a small dewpoint mirror (Meteolabor Snow White) may be used optionally, both in the SRS 400 and the new sonde. The specifications of the SRS 400 standard PTU unit and the dewpoint mirror ‘‘snow white’’ are summarized in Table 1. Additionally, a light sensor is installed at the top of the sonde (Siemens, Silicon NPN phototransistor SFH 314), which is sensitive in the spectral range from 460 to 1080 nm. The data can be used to detect the top of the clouds (see section 3).

When the dewpoint mirror is used all measurements of temperature, humidity, and air pressure are performed via temperature measurements. The sensor voltages are converted into times (durations) by the SRS 400 electronics, where fixed length pulses mark the end of each sensor signal. A complete frame is made up of eight sensor durations and lasts about 8 s on the average. In the present PTU unit, temperature is stored three times in each frame to obtain a finer time resolution.

When operationally used in Switzerland, the SRS 400 is frequently recovered and used again. With 1000 new sondes, about 2500 soundings are made (Ruppert 1999). None of the sensors requires individual calibration after use. This feature is of advantage for the new sonde. Hence, it can be used several times within a few days. The other components of the SRS 400, such as data telemetry and transponder, are omitted in the new sonde. The power supply has been replaced by a battery with a power control unit that regulates the power for all consumers (see section 2d).

Temperature and humidity sensors are placed in a duct with openings provided in the base plate and on one side of the housing (Fig. 1). An S-shaped form was chosen and successfully tested, which prevents droplets from hitting the sensors when the sonde drops through precipitating clouds. Measurements in a wind tunnel were performed to determine the wind speed in the duct of the sonde. At typical fall speeds from 5 to 6.5 m $s^{-1}$, the wind speed in the duct ranges from 3.6 to 4.7 m $s^{-1}$. The optimum sensor location in the duct resulted from tests with several thermocouples placed at different locations and comparison with an IS-4A-1680HS AIR radiosonde launched from the ground (section 3).

### *b. Sonde positioning and wind measurement*

A 12-channel receiver for NAVSTAR GPS of the U.S. Department of Defense is used for determining the sonde’s position and for offline calculation of the horizontal wind from location changes. With the Standard Positioning Service (SPS) and selective availability (SA), the average position accuracy was ±100 m only up to April 2000, and considerable wind errors resulted from SPS-based positioning. Better wind measurements are obtained by the use of a differential GPS with a fixed GPS receiver in the region of the soundings (Table 1). Raw data from GPS receivers in the sondes and at the base station are stored for this purpose, and positions as well as velocity components are calculated offline with a computer program developed by the Institut für Flugführung, Braunschweig (Biegert and Wende 2000). The differences between stand-alone GPS positions and differential GPS (DGPS) solutions were 10 m (1-$\sigma$-deviation) horizontally and 15 m vertically. GPS-based heights therefore can be regarded as an alternative to pressure measurements for height determination.

The GPS receivers are equipped with an interface to read data for GPS online correction. During our tests, VHF receivers for the acquisition of GPS corrections showed malfunctions at certain times and were not integrated in the sonde. Satellite-transmitted GPS corrections will offer new opportunities for online DGPS in the future. For this, only minor changes of the new sonde will be necessary. From May 2000 onward, SA is no longer applied to GPS signals and an improvement of winds is obvious (section 3).

### *c. Mobile telephone unit and UHF transmitter*

A GSM mobile telephone unit (GSM modem) transmits the actual GPS positions in the 900-MHz band prior to and after landing. This ensures locating of the sonde, which is necessary for data rescue and sonde reuse. The GSM modem uses the German mobile net (D1-net), which reaches almost complete coverage in Germany. Due to rather varying coverage in other European countries, GSM applicability has to be checked before measurements are made in a specific region or modems have to be installed for the available mobile phone net. The Short Message Service (SMS) is used for data transfer. This has the advantage that the data can be sent to each GSM telephone and to each e-mail address without any additional equipment being required. Based on the meteorological pressure measurement, the mobile telephone is switched on a few hundred meters above ground during descent by the central processor unit. The

TABLE 2. Sensor specification of the AIR radiosonde IS-4A-1680HS and radiotheodolite.

| Parameter | Temperature | Humidity | Pressure | Wind |
|---|---|---|---|---|
| Type | Thermistor | VIZ Accu-Lok | Capacitance aneroid | Radiotheodolite |
| Range | +50° to − 90°C | 5%–100% | 1050–5 hPa | |
| Accuracy | 0.5°C | 5% | 1 hPa | 0.4 m $s^{-1}$ (*) |
| Resolution | 0.01°C | 0.01% | 0.01 hPa | 0.1 m $s^{-1}$ |

* Standard deviation calculated from a comparison with radar data (Kolle and Kalthoff 1993).

switch-on pressure value can be set by the operator before use. As the target area is known before takeoff, the switch-on pressure value can be estimated by means of topographic maps. This ensures that the positions are safely transmitted before landing, after which local conditions (obstacles such as trees) or terrain undulations may disturb GSM communication.

A UHF miniature transmitter is additionally installed and switches on after landing to enable sonde localization by means of the handheld receiver. The 10-mW transmitter uses the 434-MHz band and has a range of 1–2 km. A separate battery supplies the device for more than 2 days, which proved very helpful in finding sondes in dense vegetation. Acoustic signals, differing between sondes, are modulated on the carrier and help to distinguish them in case of close landing locations.

### d. Central power supply and microcontroller

A single rechargeable lithium-ion battery pack is used for all electronic components. All supply voltages are controlled, and the power supply unit is connected to the microcontroller for switching off certain components after landing (e.g., mobile telephone, PTU unit).

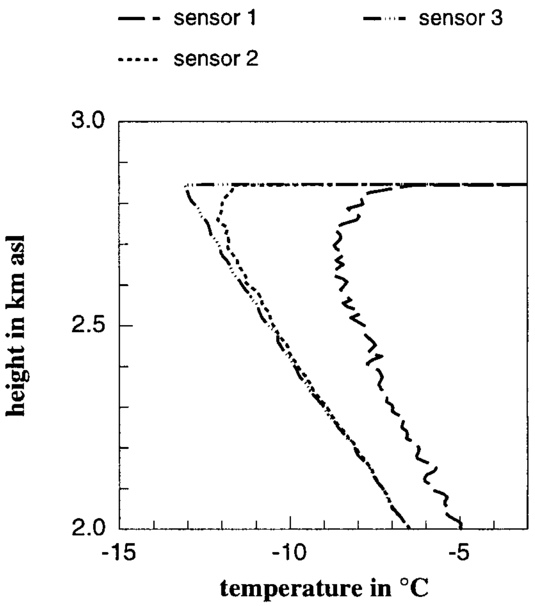


FIG. 2. Temperature profiles of sonde 2 with different sensor locations inside the duct close to (sensor 2) and far from the air inlet (sensor 1) as well as freely exposed about 10 cm outside (sensor 3).

The processor controls the acquisition and storage of all data as well as the communication with the GPS receiver and the GSM modem. The microcontroller has flash EPROM/SRAM memories for storage of the program (512 kbyte) and data (4 Mbyte), two serial interfaces, and an integrated timer unit for measuring the durations between the peak signals representing the eight readings of the meteorological PTU data. To avoid open plugs/contacts, software update and data readout are possible via the infrared serial interface and a personal computer. The data link to an optocoupler on the sonde's housing enables communication without opening the housing. Three additional ±5V differential input channels with 10-bit resolution are provided for the optional sensors.

### e. Housing, parachute, and launching device

The chosen type of housing consists of hard foam (ferma-cell), which is not flammable. Consequently, there are no emissions of harmful gases, which is important for aircraft safety reasons. The foam can be cut and machined easily, which is of advantage when producing smaller numbers of sondes. The housing consists of four layers, such that all components are easily accessible for inspection (Fig. 1). Different types of parachutes were tested. Small parachutes used for opening rescue parachutes proved to be most reliable for safe opening of the parachute. Their terminal fall speeds at mean sea level pressure range from 5 to 6.5 m $s^{-1}$ (Fig. 4) and, hence, hardly admit any damage of the housing and the sensors, which has been proved by first tests. The parachute diameter is 1 $m^2$, the drag coefficient therefore results as 1.3. The fall speed is comparable to the ascent rate of radiosondes and gives a high vertical data resolution. The kinetic energy of the sonde when hitting the ground with its mass of 950 g and a terminal speed at the ground of 5 m $s^{-1}$ is 11.8 kg $m^2$ $s^{-2}$, that is, about 25% of that of a free-falling radiosonde when the balloon bursts (Richner 1999) and about three times the kinetic energy of a lightweight radiosonde of 300 g. The housing is embedded into a net, safely connected to the parachute. Prior to deployment, the parachute is folded and placed into a small tube. It is released by a release line with a small delay in order to avoid opening close to the aircraft. Experience gained from three different aircraft shows that the release mechanism works safely and the sonde never came too close to the aircraft. Two of the aircraft are single-engine paradropping air-

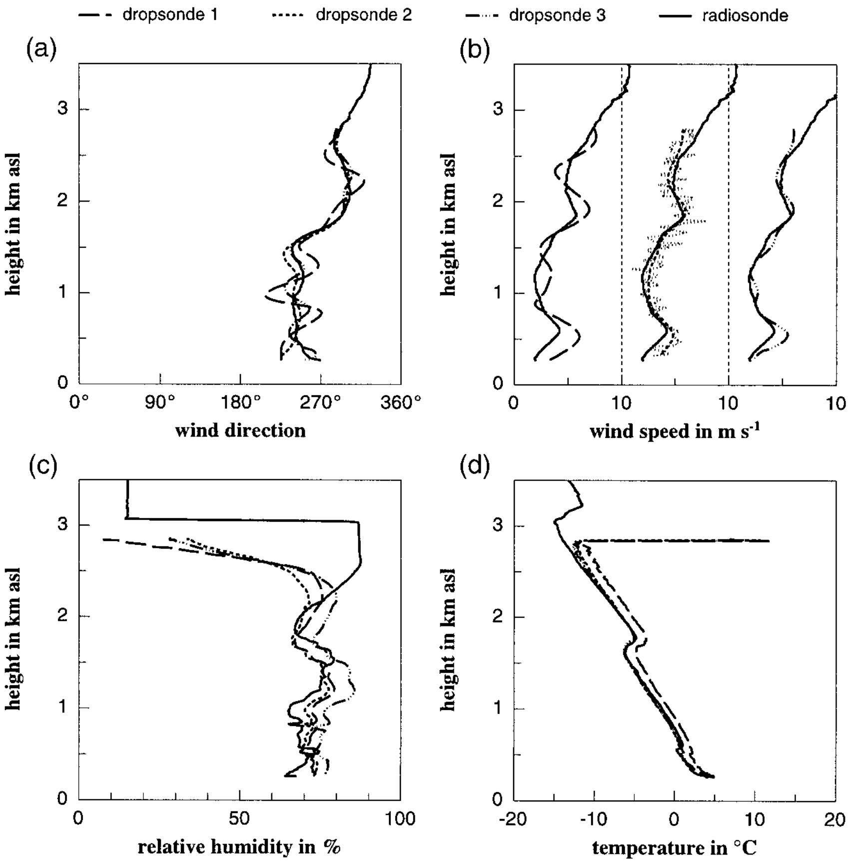


FIG. 3. Vertical profiles of (a) wind direction, (b) wind speed, (c) relative humidity, and (d) air temperature of three dropsondes and from a simultaneously launched AIR radiosonde. Wind speeds of the dropsondes are smoothed with a cutoff period of 60 s. The second diagram also includes the raw data (dotted).

craft and one is a two-engine Dornier 128, which is also equipped with meteorological and air–chemical instruments. A rack was installed in the Dornier 128 to provide external power for the 30 dropsondes prior to release. This ensures warming up of the sondes's electronics and acquisition of GPS data. After removal from the rack, the sonde switches to the internal power supply and status lights indicate whether all components are working properly.

At present, sondes were released from heights up to 4 km. The meteorological sensors have been used in the SRS sonde up to heights of 25 km and the additional components have been chosen to function reliably up to at least 10 km. When the sondes are dropped from aircraft with pressurized cabins flying at higher elevations, they could be released either through an air lock or from an unpressurized external pod. We favor the use of an external pod, a technical solution is currently being developed.

## 3. Test results and comparisons

Three prototypes of the new sonde were tested in December 1999 and February 2000 as dropsondes. As a result of the tests, minor modifications were made to optimize the temperature sensor location, the hypsometer's insulation and power control as well as the battery type and weight. Tests and an extended use of the final type of sonde were accomplished during the atmospheric convection measuring program KONVEX 2000 (Corsmeier and Kottmeier 2000). All 28 sondes were recovered after they had landed at unknown positions in the test region, a hilly countryside with a few small forest areas. In most cases, the accuracy of the SPS location, as transmitted via the GSM modem, turned out to be sufficiently accurate for finding the sonde with a good map and/or portable GPS receiver. Within a forest, the UHF miniature transmitter proved to be most valuable for locating the exact position of the sonde.

### *a. Results with differently modified sondes*

For comparison, three differently modified sondes were dropped from an aircraft within 20 s on 15 February 2000. Two of the dropsondes carried each three temperature sensors located at different sites, for example, on dropsonde 2 close to (sensor 2) and far from

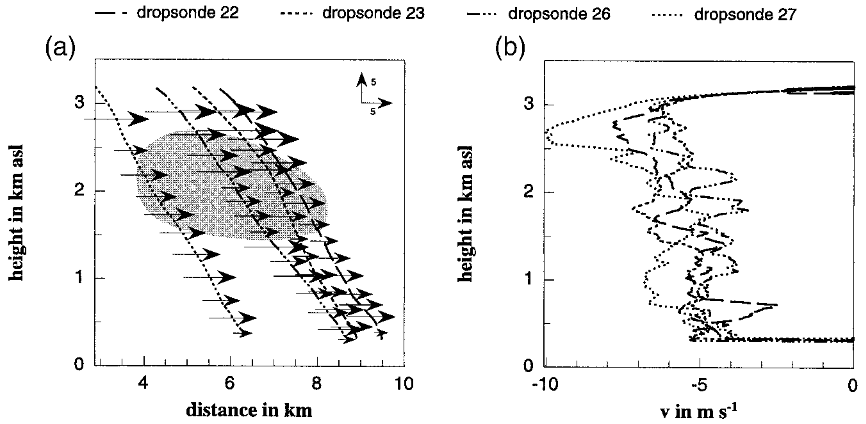


FIG. 4. Vertical structure of horizontal winds through a rapidly growing cumulus cloud derived from four dropsondes released at 3000 m within 52 s on 7 Jun 2000 near Karlsruhe. (a) The lines indicate the trajectories of the dropsondes in the *x*–*z* plane. The *x* axis is parallel to the mean wind direction. The area of the cloud is shaded. (b) Falling speeds of the dropsondes as derived from the GPS heights.

the inlet of the duct (sensor 1) as well as freely exposed about 10 cm outside the sonde (sensor 3). Additionally, an AIR radiosonde was launched from the ground at the same time. The specifications of the AIR sonde are given in Table 2. The AIR sonde trajectory was followed by an automatic theodolite system, which allows a completely independent wind measurement (Call et al. 1987). The smoothing algorithm of the system calculates running means of the wind speed over 60 s (≈300 m) at elevations below 2500 m.

Heights of the new sonde are obtained by stepwise vertical integration of pressure differences between successive data points, based on the hydrostatic equation and actual temperatures. It is essential to have at least one fix point as a boundary condition for performing the integration. Since the sondes land at different heights, the heights need to be determined from GPS height data or during recovery. When dropping sondes from an aircraft carrying meteorological instruments, such as the Dornier 128, the height measured by the aircraft can also be used for starting height calculation.

Due to the different locations of the temperature sensors on sonde 2, the sensors adjusted differently to the new environment (Fig. 2). The location of sensor 2 was used further, since it provided good shelter from water droplets and fast response to air temperature changes. The adjustment height of sensor 2 to the freely exposed temperature sensor 3 was about 150 m for the dropsonde after release from the warm interior of the aircraft.

After adjustment to atmospheric conditions, temperature differences between the AIR sonde and two of the dropsondes (sondes 2 and 3) were within the specifications, when temperature data from the sensor close to the inlet (sensor 2) were used (Fig. 3). However, the temperature of dropsonde 1 differed by about 1.5 K, which was traced back to a wrong calibration coefficient. A weak inversion at about 1700 m was well reflected by all sondes (Fig. 3). The temperature measurements also confirmed consistent pressure measurements of all sondes, since erroneous pressure would have caused a vertical shift of the temperature profiles.

Humidity data were within a range of 10%, which was within the range of errors to be expected for this type of sensor (Ivanov et al. 1991; Kolle and Kalthoff 1993). Pronounced changes were visible at similar heights. The adjustment time of the dropsonde hygristor after release is estimated to amount to about 80 s, corresponding to an adjustment layer thickness of 500 m.

Winds from the soundings were rather similar, although dropsonde wind data were based on GPS accuracy degraded by SA in this case. Low-pass-filtered wind speed data (cutoff period 60 s) of the new sondes and the raw data of sonde 2 are included in Fig. 3. The raw data indicate that sonde 2 was probably swinging below the parachute. This effect is eliminated with the parachute presently in use.

### *b. Cloud experiment*

More extensive measurements were made with 28 identical sondes during the KONVEX 2000 experiment in the Kraichgau region north of the Black Forest in southern Germany. All sondes were recovered and some of them have been used repeatedly. All of them were ready to be reused after data readout, recharge of batteries, and in some cases after minor repair. During the experiment in May and June 2000, a second GPS receiver was installed at a fixed location on a high building in Karlsruhe for offline DGPS wind calculation with a software package developed by the Institut für Flugführung of the Technische Universität Braunschweig (Biegert and Wende 2000). After giving up SA for GPS transmission just before KONVEX 2000, our setup provided for a test of location accuracy of stand-alone GPS

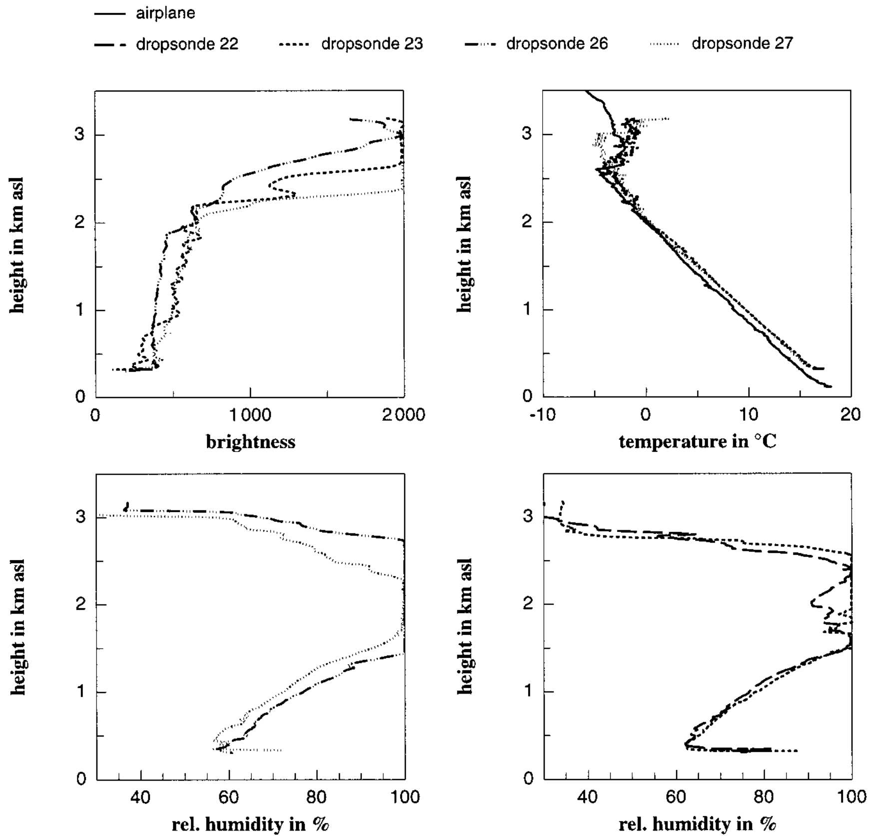


FIG. 5. Vertical profiles of relative humidity (bottom), temperature (upper right), and brightness (upper left) at different locations in the cumulus cloud. The locations of the dropsondes are given in Fig. 4. Additionally, the temperature profile measured by the aircraft between 1132 and 1149 LT is indicated.

without SA and DGPS. We found an agreement within 10 m (3-$\sigma$ deviation) in the horizontal and 20 m in the vertical. There is obviously no significant improvement for wind calculations using DGPS-based locations.

An example of a vertical cross section through a rapidly growing cumulus cloud with an aspect ratio of about 0.3 is derived from four sondes and displayed in Fig. 4, where the *x* axis is directed into the direction of the mean wind. The four sondes are dropped from the aircraft within 52 s (sonde 22 at 1235:15 LT, sonde 23 at 1235:25 LT, sonde 26 at 1235:42 LT, sonde 27 at 1236:07 LT). At that time the cloud base is at about 1.5 km above sea level (ASL) and a capping inversion can be found at about 2.7 km ASL. At this time a heating rate for the mixed layer of 0.4 K $h^{-1}$ was calculated from radiosonde data.

Temperatures inside and outside of the cloud are rather similar, except at the top of the cloud, where temperature varies by 2 K at the same level (Fig. 5). The higher temperature at the location of sonde 23 at 2.8 km ASL presumably is due to entrainment of dry and warm air from above where an inversion exists, as documented by the aircraft measurements performed between 1132 and 1149 LT.

Relative humidity and brightness data show that the cloud top is about 2750 m ASL at the location of sonde 26 (Fig. 5) and about 300 m lower at the location of sonde 22 (leading edge of the cloud), 200 m lower at the location of sonde 23 (middle), and 500 m lower at the location of sonde 27 (rear of the cloud). A video camera looking downward from the aircraft gave information on the top structure of the cloud, which, in this case, was rather compact with an intermediate less compact zone, where sonde 23 was dropped. Closer inspection of relative humidity proves the existence of certain regions with a relative humidity below 95% within the cloud (sondes 22 and 23).

The falling speeds of the sondes in the cloud are about 6 m $s^{-1}$. However, a maximum value of about 10 m $s^{-1}$ can be found at the location of sonde 27 at 2.75 km ASL, indicating a downdraft zone in the rear of the clouds. This downdraft zone could also be observed in the aircraft data performed at 3100 m ASL, where a vertical wind speed of about $w = -1.5$ m $s^{-1}$ was measured over a distance of 1.5 km. Minimum values of 4 m $s^{-1}$ can be detected at the location of sonde 26 at the heights of 1.8 km ASL and 2.2 km ASL, indicating updrafts in the center of the cloud.

Horizontal winds range between 5 and 10 m $s^{-1}$ (Fig. 4), and relative motion, that is, the deviation from the mean profile, is still slightly coherent on the scale of about 1 km (not shown). Winds are consistently larger above the cloud tops and relative winds are opposite to the mean flow near cloud base at the leading edge (sonde 22), causing a horizontally convergent flow pattern there.

## 4. Conclusions

Both during tests and in practical use, the new aerological sonde turned out to be a reliable measuring system meeting the specifications it was designed for. It is of proven suitability for studying mesoscale fair weather phenomena in regions with most places on the land surface being accessible for sonde recovery. No principal measurement problems have to be expected for soundings in the upper troposphere, except that dropsondes in this case would need proper release devices on the aircraft. Future tests will comprise measurements with sondes passing heavy rain or hail as well as deep convective clouds with strong electric fields.

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The new aerological sonde is protected by Patent No. 198 52 797 by the German Patent- und Markenamt granted on 30 June 2000.

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