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Two New Types of Ultrafast Aircraft Thermometer

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ABSTRACT

A new version of an ultrafast aircraft resistance thermometer (UFT-F) with a time constant of the order 10^{-4} s, for use in both cloudy and cloudless air, is described. It evolved from an earlier version (UFT-S). Its sensing element is similar to that in UFT-S and consists of a 5-mm-long and 2.5-μm-thick platinum-coated tungsten wire, located on a rotatable vane behind a thin vertical rod that protects the sensor against direct impact of cloud droplets and other objects. Such construction introduces much smaller thermal disturbances than do more massive housings of other types of immersion thermometers and permits taking full advantage of low thermal inertia of the sensing wire. However, aerodynamic disturbances created by vortex shedding from the protective rod induce adiabatic fluctuations of temperature, which appear on the temperature records as ''noise.'' In the case of the UFT-S the level of this noise has become intolerable at airspeeds of about 40 m s^{-1}, limiting applicability of this instrument to slow aircraft or gliders. For UFT-F the shape of the protective rod has been redesigned and endowed with a special system of reducing aerodynamic disturbances behind it, which made it usable at airspeeds up to 100 m s^{-1} in cloudless air or warm clouds. For use in supercooled clouds, a special variety of UFT-F (denoted here UFT-D) has been designed. As in its predecessor, its sensing element is a 5-mm-long, 2.5-μm-thick, platinum-coated tungsten resistive wire protected against impact of cloud droplets by an airfoil-shaped rod, but all its icing-sensitive parts are electrically heated to prevent buildup of ice. This modification required a total change of mechanical structure of the instrument. Tests during the Third Canadian Freezing Drizzle Experiment showed that UFT-D can perform fairly well in water clouds supercooled down to at least $-8°$C and that its heating system introduces no intolerable disturbances into the record. Use of UFT-D in ice or mixed clouds is limited by the fact that the protective rod is not effective enough against ice crystals bigger than about 200 μm, which can quickly destroy the delicate sensing element.

The paper gives details of construction as well as results of wind tunnel and in-flight tests of these instruments.

1. Introduction

In recent years a number of cloud physicists paid attention to small-scale inhomogeneities in clouds, recognizing that they may play a crucial role in many fundamental microphysical and dynamical processes. Knowledge of the finescale structure of dynamical and thermodynamical parameters in clouds (particularly in the convective ones) is fundamental for understanding the dynamics of entrainment and mixing processes. In turn, the latter control a good deal of both the microphysics and bulk dynamics of these clouds. Particularly important questions refer to the time-and space scales of the inhomogeneities created by early stages of mixing, as well as to the speed of their evolution toward full homogenization of the cloudy air (Baker 1992; Malinowski et al. 1994; Haman and Pawlowska 1995). Small-scale inhomogeneities of temperature and humidity may result in high local supersaturations, creating conditions for the formation of a large droplet ''tail'' of the spectrum and subsequent speeding up of the coalescence process.

Unfortunately, the finescale processes, scales of order 10^{1}–10^{-3}m, are extremely difficult to investigate. Resolution of remote sensing instruments is much too poor for this purpose, and that of the in situ techniques is in most cases also not good enough. Until now, the best results have been obtained by means of certain fast for-

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ward-scattering spectrometer probes (FSSPs), with respect to interdroplet distances where a resolution of a fraction of a millimeter has been achieved (Baumgardner et al. 1993; Brenguier 1993), but for measurements of temperature or humidity it is much worse. In the case of temperature the indications of typical immersion airborne thermometers are strongly contaminated by the influence of their supports and housings, and their effective time constants are usually of the order 10^{-1} s or more (e.g., Friehe and Khelif 1992). For typical airspeeds of research aircraft this permits a spatial resolution of the order 10–100 m; radiometric instruments are faster, but their measurements are averaged over relatively big volumes, and thus their spatial resolution is not much better (Lawson and Cooper 1990).

In efforts to overcome these limitations the authors of the present paper developed a new airborne immersion thermometer with the sensor protected against impact of cloud droplets, which they believe to present an essential progress in that respect. It was named UFT (ultrafast thermometer) and described in detail in the paper by Haman et al. (1997). The time constant of its sensing elements is of an order 10^{-4} s (which permits spatial resolution down to centimeters—fairly close to Kolmogorov scale), and the thermal influence of the supporting parts, as well as the antidroplet protection, is relatively small. Some preliminary results of measurements made with this instrument can be found in the papers by Haman and Malinowski (1996a,b). Unfortunately, aerodynamic disturbances behind the antidroplet protection induce adiabatic fluctuations of temperature, which at airspeeds exceeding 40 m s^{-1} become intolerably strong. This limits the applicability of this instrument to slow aircraft or gliders; on faster aircraft some filtering of the record becomes necessary, which results in considerable loss of the spatial resolution.

This instrument started a bigger family of ultrafast thermometers based on similar principles for use on various platforms and in various conditions, which is now under development. In order to introduce a certain logical rule in naming various members of this family we decided to refer to this early instrument as UFT-S (S for slow), reserving the acronym UFT for the whole family.

In the present paper a version named UFT-F (F for fast) and its variety UFT-D (D for de-iced) are described. UFT-F was designed for use on faster aircraft at airspeeds up to 100 m s^{-1} or perhaps more. In order to reduce this aerodynamic ‘‘noise’’ the antidroplet protection was redesigned and endowed with a suction system that effectively damped excessive aerodynamic disturbances in its wake.

Successful preliminary observations made with use of UFT-S and UFT-F have shown that in mixing regions of cumulus clouds 1–2-K jumps of temperature over distance of few centimeters are often encountered (Haman and Malinowski 1996a, b). Existence of such jumps suggests the presence of high local supersaturations, in which cloud droplets can presumably grow by condensation to drizzle size, or at least to a size that permits effective coalescence and development of a bimodal spectrum of droplets (Korolev and Isaac 2000). The problem is interesting not only from the point of view of pure cloud physics, but also has an important practical aspect, since supercooled drizzle is an essential factor in icing of aircraft and surface objects (see, e.g., Marwitz et al. 1997). Thus, extending ultrafast temperature measurements to supercooled clouds became an interesting challenge to people working in this area. A suggestion to undertake such an effort was made to the authors by A. Korolev in connection with the Third Canadian Freezing Drizzle Experiment (CFDE3) held in winter 1997/98. Though some successful flights in weakly supercooled ($-1° \div -2°$C) clouds with low liquid water content were already made with UFT-S and UFT-F, it was obvious that in significant icing conditions these instruments will quickly cease to work. This gave rise to the idea of designing UFT-D. It works on a principle similar to that of UFT-F, but has a different mechanical design, which permits all of its icing-sensitive parts to be electrically heated.

UFT-D is a fairly new instrument, and experience with its exploitation is rather limited. It seems at present that its greatest drawback is vulnerability to big (diameter over 200 μm) ice crystals often present in many supercooled clouds, which limits its applicability to specific meteorological conditions. Nevertheless, preliminary results achieved with its use look promising enough to justify the presentation of this instrument to the wider cloud physics community.

In the following, the constructions of these instruments as well as details of their tests in wind tunnels and in flight are given.

2. Construction of the UFT-F sensor

The basic design of key mechanical components of the UFT-F thermometric unit is shown in Fig. 1a. It is very similar to the UFT-S described by Haman et al. (1997), with few but essential differences. The device consists of a light, well-balanced pivoting frame with an attached wind vane. The front part of the frame is a thin, suitably shaped rod, which acts as an antidroplet shield, and mechanical protection for the sensing element, an ultrafine thermoresistive wire. The vane fixes the position of the shielding rod upwind with respect to the local instantaneous flow. The sensing element (1) is a thermoresistive, platinum-coated (9% platinum) tungsten wire, 2.5 μm thick and 5 mm long. At room temperature its resistance is about 50 Ω, depending on individual manufacturing and mounting differences. The wire ends are soldered to 0.3-mm-thick, Teflon-insulated copper supports (2), hidden in 0.8-mm stainless steel tubes (3). These tubes are covered with electrically insulating lacquer in order to protect the supports (2) against shunting by cloud water, which might in-

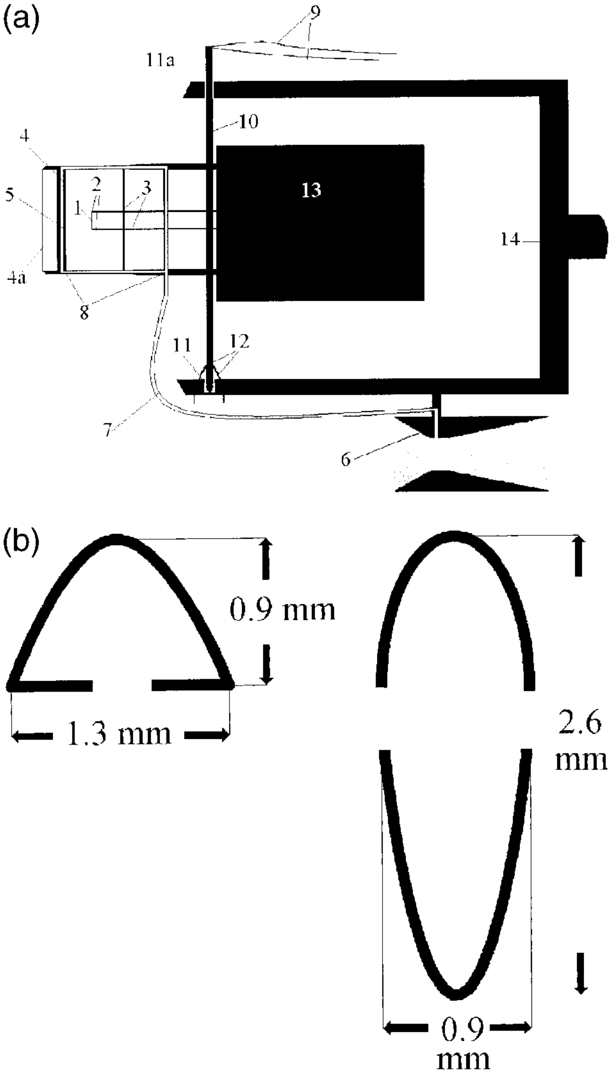

FIG. 1. (a) Schematic view of the UFT-F sensor: (1) sensing element (platinum-coated tungsten wire, $\varnothing$ 2.5 μ, length 5 mm); (2) Teflon-insulated copper supports; (3) stainless-steel tubes; (4) airfoil-shaped protecting anti-droplet rod made of stainless steel; (4a) additional protection in form of 0.25-mm nylon string (in newer versions of the instrument); (5) slots for suppressing wake eddies and water removal from the rod; (6) Venturi nozzle for creating suction; (7) elastic tube connecting the sensor frame with the Venturi nozzle pneumatic ducts in gray; (8) sensor frame; (9) insulated copper connectors; (10) shaft; (11) ball-point bearing; (11a) sleeve bearing; (12) shaft bumpers; (13) vane, (14) supporting fork. (b) (right) Cross section of an antidroplet protective rod of UFT-F [part (4) in (a)] compared with (left) that of UFT-S.

cidentally creep to these points. The sensing wire is located 6.5 mm behind the rod (4), which protects it against wetting by cloud droplets as well as from destruction by other objects like insects, sand grains, etc. In contrast to the UFT-S (see Fig. 1b), where the rod is made of a 1.1-mm-thick, stainless steel tube deformed to a hollow, triangular cross section with a 1.3-mm-wide back wall, the hollow rod of UFT-F is airfoil shaped. Its cross section is symmetric, 2.6 mm long, and 0.9 mm thick. Just behind its camber there are two 12-mm-long and 0.35-mm-wide slots (5) where water is suctioned off with a big Venturi nozzle (6) through a flexible plastic tube (7) and hollow parts of the frame (8). Their role is to suck off the close-to-the-surface layer of air in order to damp the wake eddies that form behind the rod and are responsible for aerodynamic noise in the temperature record (analog of solution used in aircraft wing designing for few decades). They also serve to remove water that collects on the rod during flight in clouds. In recent versions of the sensor a 0.25-mm-thick nylon string (4a), located 3 mm ahead of the rod (similar to that in the UFT-S) has been added. Wind tunnel and in-flight tests have shown that this improves both the eddy-damping and antidroplet effectiveness of the rod. Two copper connectors (9) connect the supports electrically to a three-wire extension line. They are made of soft, flexible wires so that the frame can rotate freely around the stainless steel shaft (10) on a ball-point bearing (11) and a loose sleeve bearing (11a) with negligible friction. The shaft has two bumpers (12), which limit its turning angle to about 40° and prevent twisting of the connectors. The remaining mechanical elements of the frame, aimed at making the construction sufficiently stable, are made of brass or stainless steel. The flat (or V-shaped or double-tailed, in some older versions) vane (13) is made of stiff, 0.5-mm-thick plastic sheet reinforced with balsa wood ribs. The bearings of the rotatable frame are placed at the ends of a strong, forklike support (14), which should be located in an aerodynamically undisturbed place on the aircraft (preferably on a boom), with the shaft of the wind vane directed vertically. Although the vane has only one degree of freedom, it can keep the sensing element within the protected area, in case of moderate variations in pitch and roll angles that can occur in typical flight conditions.

The three-wire extension line connects the sensor to the electronics box so that the sensing wire becomes a branch of a typical Wheatstone bridge. In the particular unit used by the authors its primary output was adjustable to about 200, 300, or 400 μV K^{-1} depending on the expected range of temperatures. The outgoing signal is amplified (200 times in our case) and conditioned with an anti-aliasing low-pass filter adjusted to the characteristics of the recording unit in use. Various individual UFT-F devices may differ in secondary details. Figure 2 shows a general photographic view of UFT-F in comparison with the UFT-S.

In case of any damage [e.g., breaking of the sensing wire (1)], the whole sensor is usually exchanged. Construction of the support (14) permits doing it in only a few minutes, even in field conditions. Conversely, exchange of the sensing wire is technologically a fairly complex procedure, which must be made in laboratory conditions using special tools and takes a skilled technician about an hour to complete.

Let us notice an essential difference between the UFT-F and the UFT-S water removal systems. In the

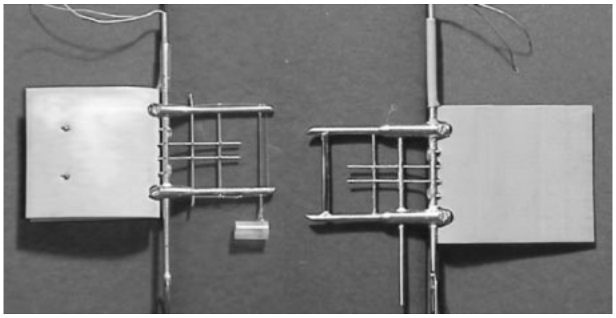

FIG. 2. (right) General view of the UFT-F sensor (version without nylon string) compared to (left) the UFT-S.

latter, the water is sucked off through two or three small, round, 0.4-mm holes in the back wall of the rod by means of a small Venturi nozzle, 10 mm long and 6 mm wide, attached directly to the rod and giving suction of about 20 hPa. In UFT-F, where the surface of the slots is about 40 times greater, and for effective damping of wake eddies the suction must be of the order 100 hPa, a much bigger Venturi nozzle has to be applied. A few of them, slightly differing in details but representing approximately the same effectiveness, were manufactured in the course of the UFT-F development. All were about 10 cm long and 3 cm wide, and thus had to be mechanically separated from the rotatable frame of the sensor, being connected with it by means of a soft, flexible plastic tube. This complication makes UFT-F inconvenient for use on slower aircraft, on which the UFT-S performs sufficiently well.

Most of the technical solutions of the UFT-F (UFT-S as well), particularly the shape and dimensions of the protective rod, were selected empirically under the guidance of ‘‘educated guess’’ and of results of tests performed with few initially considered different variants. Some trials of a more theoretical approach proved to be very cumbersome and had problematic practical value in view of unavoidable simplifications. Also, mechanical properties of the frame (e.g., period of its free oscillations and their damping) could be only roughly estimated in a theoretical way. Thus, experimental testing of performance of various parts of the instrument and estimating their influence on its general performance has been found to be a more appropriate approach. Results of such testing are presented in the following sections.

3. Laboratory testing of UFT-F

Laboratory tests of UFT-F were directed toward answering the four following questions.

1) How well does the new antidroplet rod damp the aerodynamic noise at airspeeds up to about 100 m s^{-1}?
2) How effectively does it protect the sensing wire?
3) How strong is its thermal influence on the sensor?
4) How does the thermal response of the sensor depend on its deflection from the streamline?

The importance of the first three questions is obvious, while the importance of the last follows from the fact that some incidental oscillations of the vane around the airflow direction can occur in turbulent air and may be responsible for part of the noise if the response of the sensor (e.g., its recovery factor) is strongly dependent on the deflection angle.

To answer the first question, a special support for UFT-F and its big Venturi nozzle has been constructed and installed in the low-turbulence wind tunnel of the Warsaw Technical University. This tunnel, with a cross section of 265 mm × 600 mm, enables a generation of flow with airspeed up to 90 m s^{-1}, turbulence level not exceeding 0.2% relative rms, and nearly ‘‘top hat’’ profile. The installation permitted measurements of airspeed and suction intensity in terms of pressure deficit and airmass-flow value. All manufactured sensors were individually tested at various airspeeds, with suction subsequently switched on and off. Since, in the manufacturing process of UFT-F, some steps cannot be fully standardized, differences between various individual UFT-Fs were observed; excluding a few definitely defective ones, most of them performed fairly well. Even without suction the measured amplitude of the noise at airspeeds of about 90 m s^{-1} was not greater than 0.5 K, peak to peak. This is more than two times lower than in the case of the UFT-S, with a considerable part of it evidently following from weak internal turbulence in the tunnel as well as from electromagnetic disturbances generated by various outer sources present in the building. With suction on, this amplitude could usually be reduced two- to threefold. An example of such a test is presented in Fig. 3. As shown in the following section of this paper, in-flight tests performed on the Do-228 aircraft confirm this low level of noise.

The question of protective effectiveness of the new rod is more difficult to answer. A priori, with its laminar shape, it can be expected to be less effective than the old, triangular one, and some residual wetting of the sensing wire may take place. However, certain incidental observations mentioned already in Haman et al. (1997) suggested that the 2.5-mm-thick wire may be practically unwettable at higher airspeeds. To test it more precisely a special laboratory stand was designed on which the sensing wire was exposed to an airstream containing water droplets with a size spectrum corresponding to a typical convective cloud and observed by a stereo microscope with 35-fold magnification. Observations have shown that at airspeeds below about 20 m s^{-1} water collects on the wire in the form of droplets, which were growing to a certain critical size before being blown away. At higher airspeeds such collection of water has not been observed, though formation of a thin, practically invisible film, a few tenths of a micrometer thick, could not be excluded. No realistic way of detecting

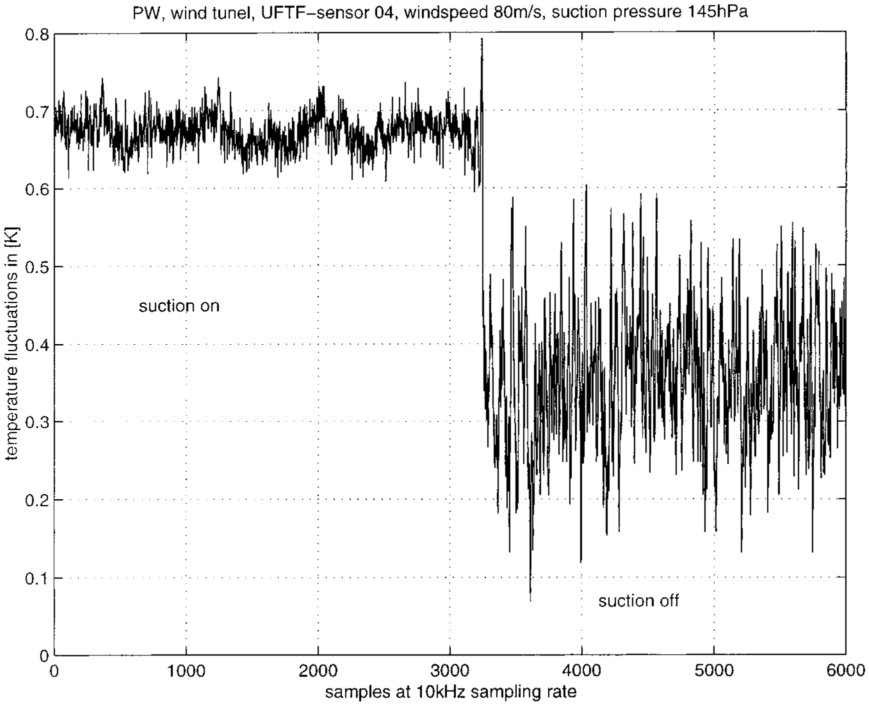

FIG. 3. Example of a record from wind tunnel tests of the UFT-F sensor at an airspeed of 80 m s^{-1}. Notice the variation in the noise level and mean temperature value between the "suction on" and "suction off" regimes.

such a film has been found. Its presence could be indirectly suggested in flight tests by rapid, transient drops of temperature (wet-bulb effect) systematically appearing after leaving the cloud but not before entering them. Some cases of such temperature drops lasting a few milliseconds seems to be found in certain flights (Fig. 4), but unfortunately the statistics are too limited to yield a credible answer regarding whether this is a wet-bulb effect of the wetted sensor or a real, noninstrumental phenomenon resulting from mixing of cloudy and outer air at the edge of the cloud. In other cases of passing through clouds no such effects were found, confirming the effectiveness of the protective rod in these particular cloud crossings. Let us notice that the time τ of evaporating a uniform water film of thickness d in air with wet-bulb depression ΔT can be estimated from the following expression, which results from combining the equation for the diffusional evaporation/condensation on the wire with the psychrometric relation:

$$\tau = \frac{L d \delta \rho}{\kappa \mathrm{Nu} \Delta T},$$

where L is the latent heat of water condensation, d is the sensing wire diameter, ρ is the density of water, κ is the heat conductivity of air, and Nu is the Nusselt number. Allowing approximately (in SI units) $L = 2.5 \times 10^6$, $\rho = 10^3$, $\kappa = 2 \times 10^{-2}$, $d = 2.5 \times 10^{-6}$, and $\mathrm{Nu} = 2$, we find, that if the observed temperature drop visible in Fig. 4 were essentially due to a wet-bulb effect, recorded values of τ and ΔT—about 5 ms and 1.3 K, respectively—may suggest hypothetical film thickness of about 0.05 μm.

Since wetting may or may not be present, depending on a particular spectrum of cloud droplets, the problem needs further in-flight investigations. As already mentioned in section 2, a 0.25-mm string placed 3 mm ahead of the rod, similar to that successfully used on the Vane Thermometric Unit (VTU) (Haman 1992) and UFT-S (Haman et al. 1997) for eliminating residual wetting of the sensing wire, has been installed in recent series of the sensor. Tunnel tests have shown that it does not increase the aerodynamic noise (and even improves its damping), and in a few flights with its use no evident signs of wetting have been observed, suggesting that this might be a successful solution.

Another problem is the effectiveness of the protective rod against precipitation particles. Limited experience, a few minutes of flying in precipitation zones, suggests that the protection is sufficient against raindrops, but not against big ice crystals or graupel, which usually destroyed the sensing wire shortly after entering their zone. Probably, asymmetric and relatively big ice particles struck by the rod may move behind the rod, destroying the delicate sensing wire. Big particles may also deflect the vane, leaving the sensing wire unprotected for a short period, particularly in the older versions with V-shaped tails.

Tests of the thermal influence of the rod have been

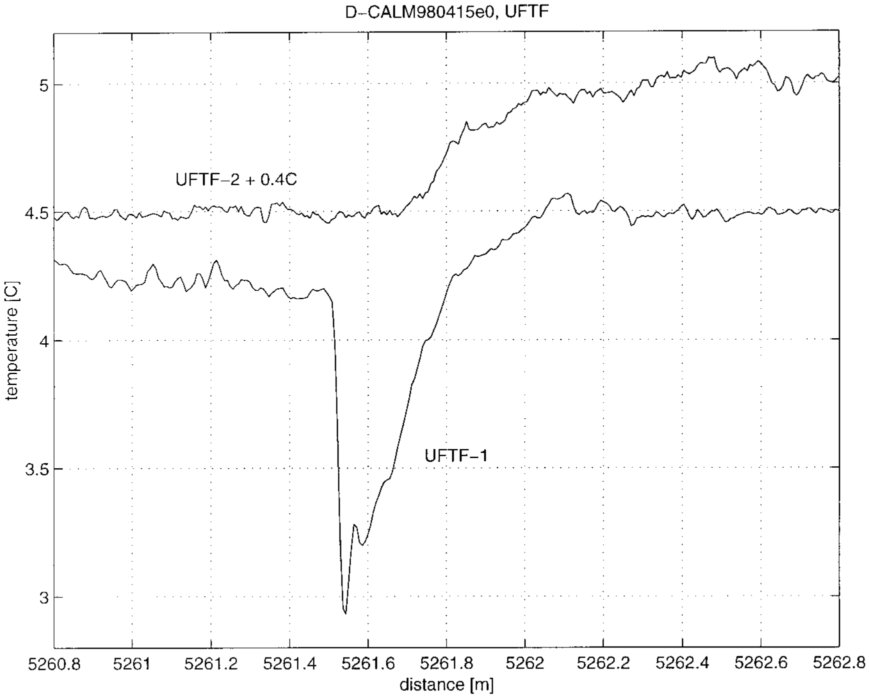

FIG. 4. Fragment of a temperature record taken with two UFT-F sensors in flight through Cu med cloud at an airspeed of 70 m s^{-1}. A drop of temperature lasting about 5 ms recorded with UFT-F1 might result from a wet-bulb effect on the sensing wire wetted while passing the cloud. Distance on the horizontal scale is measured from the beginning of recording.

performed in the DLR wind tunnel with a specially designed UFT-F, which permitted heating of the protective rod by means of electric current flowing through it. The increase of its temperature above the outer value was measured by means of a thermocouple, with one junction fastened with epoxy glue to the rod and the second one exposed to the free airflow. Results of this test are presented in Fig. 5, showing that for an airspeed of 47 m s^{-1} (maximum available) the rod temperature excess induces an increase of temperature indication not exceeding 5% of its value. This is probably a considerable overestimate, resulting from the fact that the temperature excess of the thermocouple junction ventilated by air from one side and isolated with glue from the rod, could be much lower than that of the rod itself; additionally, it has been noticed that this effect decreases with increasing airspeed. In fact, estimates following from inflight experience with UFT-D at airspeeds of 70–100 m s^{-1} strongly suggest that thermal influence of the rod does not exceed 2%–3%. Let us recall (Haman et al. 1997) that the thermal inertia of the rod participates in the combined thermal inertia of the sensor in the same proportion.

In order to answer the last question, regarding sensitivity to angular deflection, a special unit has been designed and tested in the wind tunnel. It consisted of a slightly modified UFT-F sensor, with the vane removed, which could be turned around its shaft by a system of strings, and with an angular position that could be measured with a simple electric device. The sensor was then turned in the airstream back and forth from one stream-perpendicular position to the other, passing through the stream-parallel position, which is the working one of operational UFT-F. There was also a possibility of deflecting the sensing wire from the vertical symmetry plane of the sensor in order to estimate the effect of small inaccuracies that may occur while assembling the device.

A typical result of this experiment is shown in Fig. 6. With the suction on (Fig. 6a), the temperature anomaly in the wake is positive (in contrast to the results found for the UFT-S) and it shows only a slight wavy shape. With the suction off the anomaly becomes similar to the UFT-S (Haman et al. 1997, their Fig. 5); it is V-shaped and wavy with a negative value in the center of the wake (Fig. 6b). This explains the shift of indicated average temperature values between ‘‘suction on’’ and ‘‘suction off’’ regimes visible in Fig. 3. Experiments with asymmetrically positioned wire have shown that details of the shape of a temperature anomaly are sensitive to the position of the wire with respect to the protecting rod. These findings may explain differences in the noise level and reactions to switching off the suction found in various individual UFT-Fs manufactured until now; even small inaccuracies in manufacturing and positioning the protecting rod may cause a considerable increase in the noise and a change in its structure. It also shows that determining a universal re-

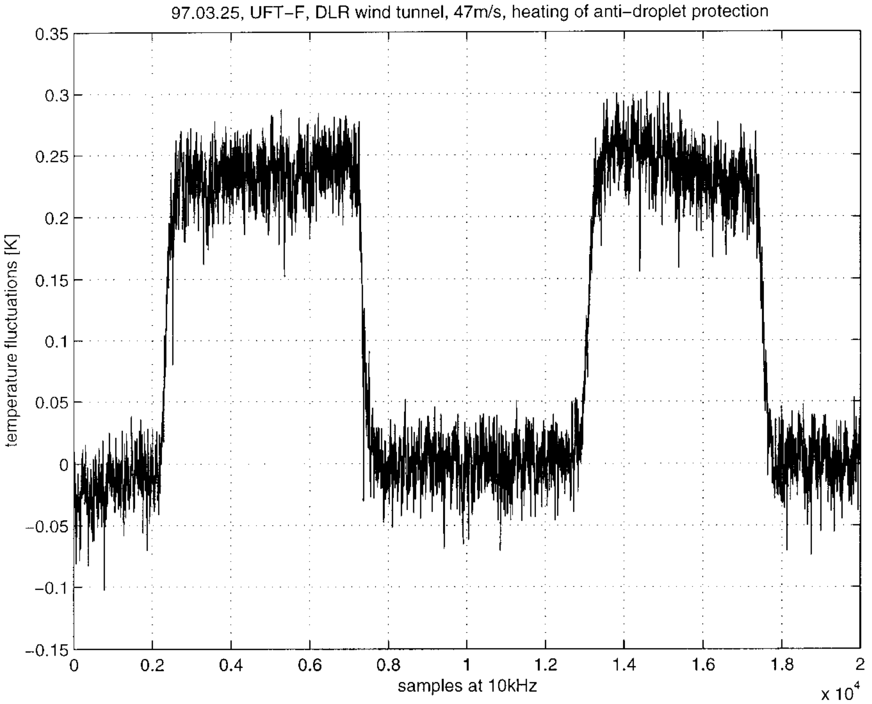

FIG. 5. Detrended record from a wind tunnel test with UFT-F, with the protecting rod intermittently heated to a temperature about 5.5 K above the ambient value. Wind speed is 47 m s^{-1}. As shown by the record, this heating results in an increase of the average indicated temperature of about 0.25 K, i.e., less than 5% of the heating value. See text for details and discussion.

covery factor for this instrument may become difficult. Its value may vary from one individual UFT-F sensor to another and additionally it may be sensitive to the form of the wake and thus dependent on the airspeed.

The fact that temperature indications close to the central point of the anomaly are strongly dependent on the angular position of the sensor may cause an increase in the noise due to vibrations of the vane, particularly in a turbulent atmosphere. Theoretical analysis of such vibrations is difficult, since they depend not only on aerodynamic properties of the vane but also on elasticity of the pneumatic tube and electric connections as well as friction in the bearings (though the latter seem negligibly small), both of which may additionally vary with changes of ambient temperature. An experimental approach to this problem in wind tunnel tests with artificially induced vibrations of the vane also appeared to be technically difficult, and respective experiments gave ambiguous results. They showed, however, that at 90 m s^{-1} the resulting noise does not exceed 0.35 K peak to peak even with unrealistically strong oscillations (which could be expected after inspection of Fig. 6).

As follows from the above analysis, the aerodynamic noise is a fairly complicated phenomenon. However, from the practical point of view, the resultant noise level is more essential than the nature of its components, and thus it has been decided that a wind tunnel test of each individual UFT-F should be performed as a basis for accepting it for operational use on an aircraft. If at airspeeds up to 90 m s^{-1} the noise is lower than 0.2 K peak to peak and its behavior (except amplitude) while switching the suction on and off remains similar at various airspeeds, the sensor is assumed to be good; otherwise it is rejected as defective.

4. Conclusions from preliminary flight experiences with the UFT-F sensor and perspectives of its further development

The UFT-F is a fairly new construction and experience with its exploitation is rather limited. It has been tested mainly on DLR Oberpfaffenhofen research aircraft Do-228, on which eight test and research flights have been performed to date. During these flights the UFT-F was mounted in a typical Particle Measuring System, Inc. (PMS) container, which was fixed under the wing (Fig. 7). On Do-228 the output was conditioned with a 3-kHz low-pass filter and digitally recorded with a 10-kHz sampling rate. Suction applied to the protecting rod (measured with respect to outer static pressure) varied from 62 hPa for 70 m s^{-1} to 117 hPa for 90 m s^{-1}. As an example, results of the tests of the level of aerodynamic noise at airspeeds of 70 and 90 m s^{-1}, performed during a flight made on 14 May 1998, are shown in Fig. 8. Note that even at 90 m s^{-1} the noise does not exceed ±0.1 K, an order of magnitude less

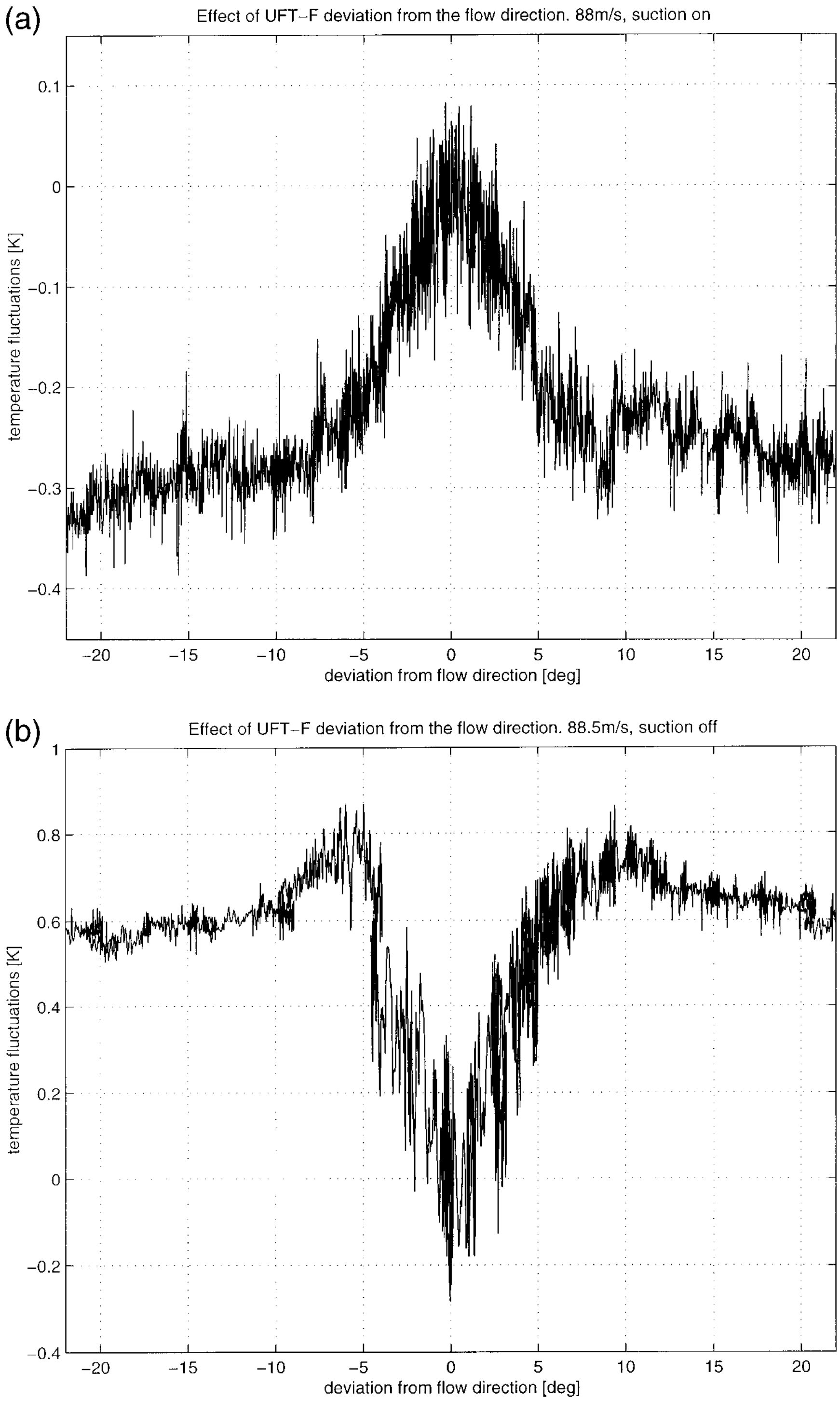

FIG. 6. (a) Record of temperature taken with UFT-F as a function of the angle of deflection of the vane from the airflow direction with suction on. Standard deviations of noise level for the sensing wire in protected and unprotected positions are respectively 0.043 and 0.023 K. (b) As in (a) but with suction off. A slight convexity and asymmetry of the curves in both figures result from deviations of the airspeed from top-hat profile and disturbances of the flow created by support of the sensor inside a relatively narrow wind tunnel.

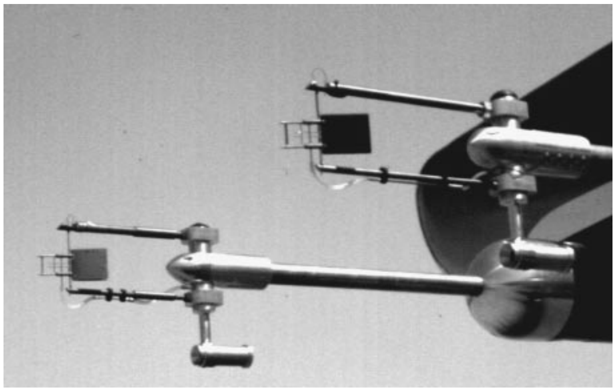

FIG. 7. Two UFT-F sensors in PMS canisters under the wing of the DLR Dornier Do-228.

than that of the UFT-S. It is worth noting that dependence of the noise level on airspeed is much weaker for the UFT-F than for the UFT-S (where it increased roughly with the square of the airspeed), though it varies from one individual sensor to another. The noise on the aircraft is usually lower than in the wind tunnel (in the case of certain particularly good sensors it was weaker than 0.1 K peak to peak), which probably follows from the fact that the wind tunnel is not free from its own small-scale turbulence, and the record may be additionally contaminated there by various external electromagnetic disturbances from electric devices in the building.

An example of a record from a research flight is shown in Fig. 9. On this flight two UFT-Fs were installed side by side about 70 cm from each other. Notice striking differences in temperature records taken in such a small distance one from another, as well as rapid variations of temperature along the flight line, which confirm earlier results from UFT records (Haman and Malinowski 1996a,b). The distance between successive samples is only about 7 mm. Although variations of temperature over such distances are recorded with strong distortions, caused by the inertia of the sensor as well as the 3-kHz antialiasing filter, the presence of sharp temperature jumps could be at least qualitatively detected.

Calibration of the UFT-F sensor presents some problems. Slight changes in the basic resistance of the sensing wire, resulting presumably from corrosion of tungsten in places with defective platinum coating, are sometimes observed, so that calibration may not be very

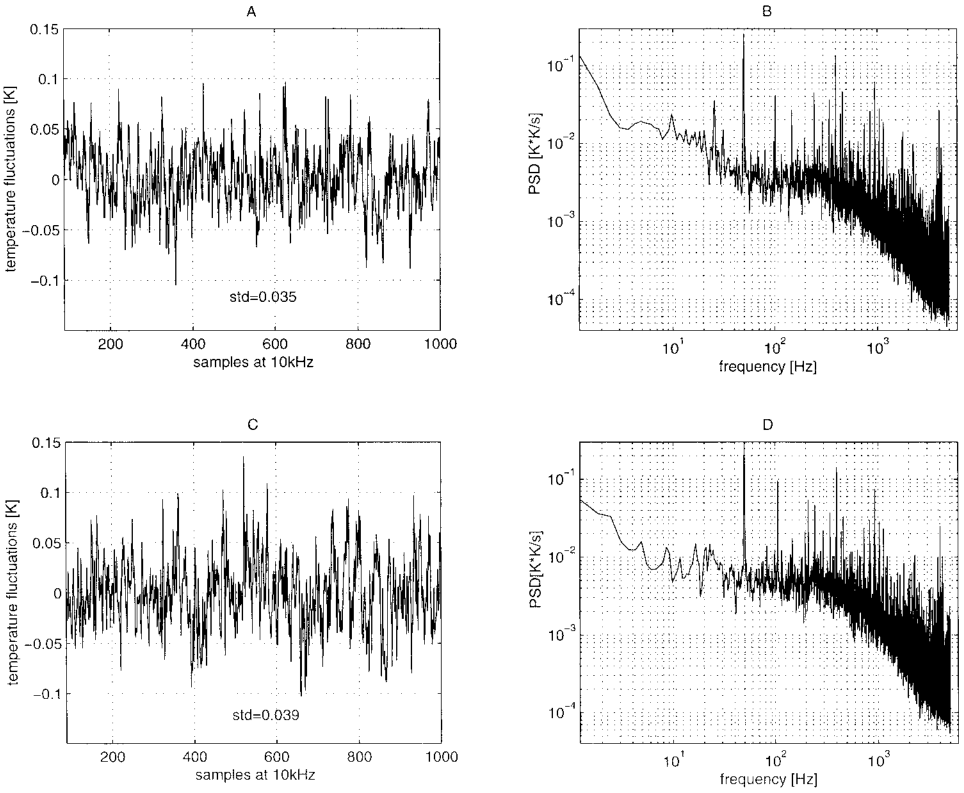

FIG. 8. Effects of the airspeed on the noise level of UFT-F. (a) An example of temperature fluctuations at 70 m s^{-1} in calm air. Standard deviation of temperature fluctuation for the whole record is given in the figure. (b) Power spectra of the record, of which the segment is presented in (a). Spikes of 50 Hz and 400 Hz generated by the aircraft AC power network and their higher harmonics are clearly visible. The peak at about 4 kHz presumably reflects the characteristic frequency of aerodynamic noise. (c) As in (a), but for 90m s^{-1}. (d) As in (b), but for the record shown in (c).

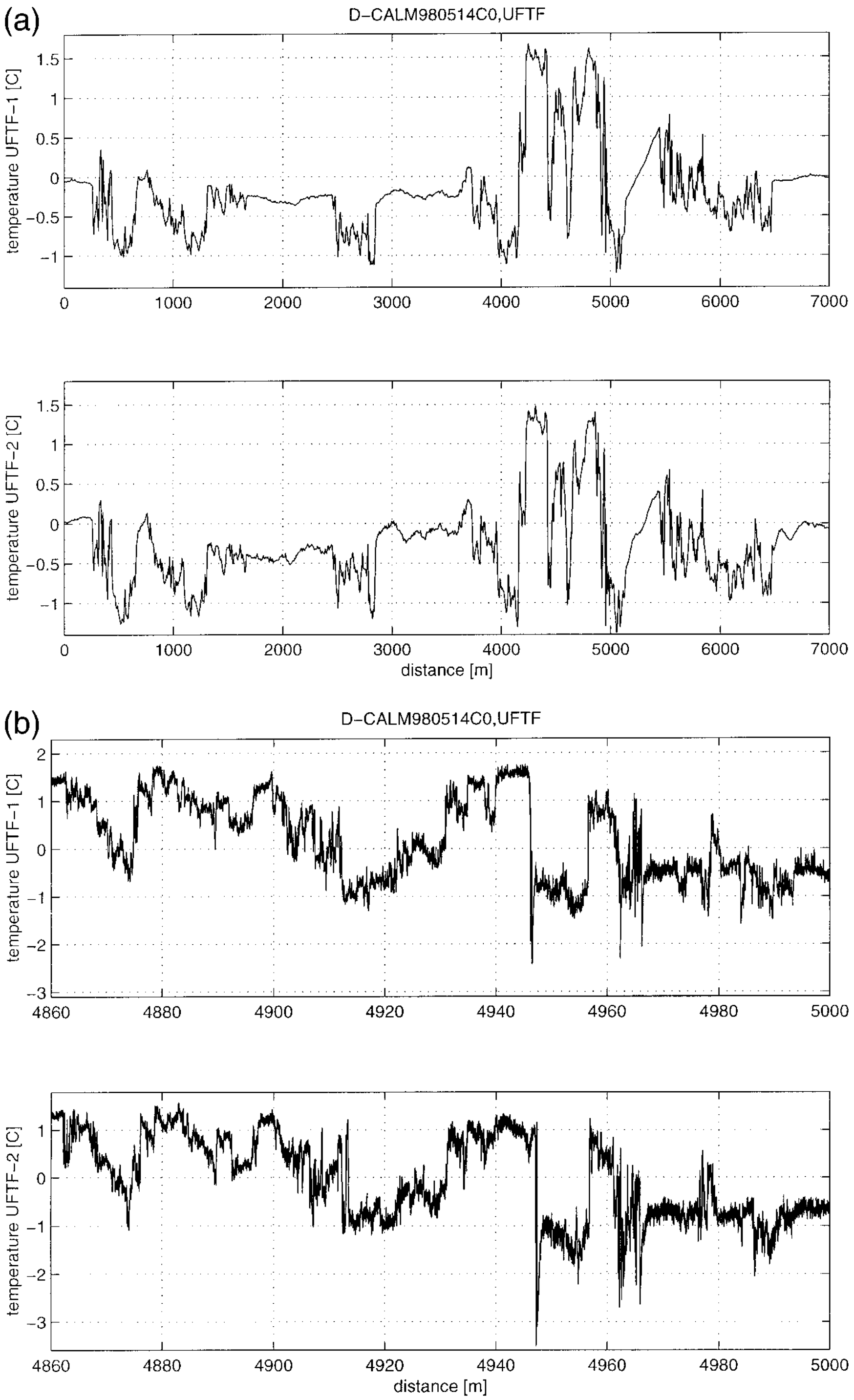

FIG. 9. An example of a double UFT-F record from passing a Cu med cloud at 70m s^{-1}. All distances measured from the beginning of the record. (a) The whole pass averaged to 10-Hz sampling frequency. (b), (c) Expanded segments at full 10-kHz sampling frequency. Distance between successive samples is about 7 mm, while sensors are 70 cm one from another, side by side. Notice the time shift of analogous temperature features in (c) between UFT-F1 and UFT-F2, resulting presumably from the inclination of the front surface to the direction of flight. Differences in temperature ranges between 10-Hz and 10-kHz data result from averaging.

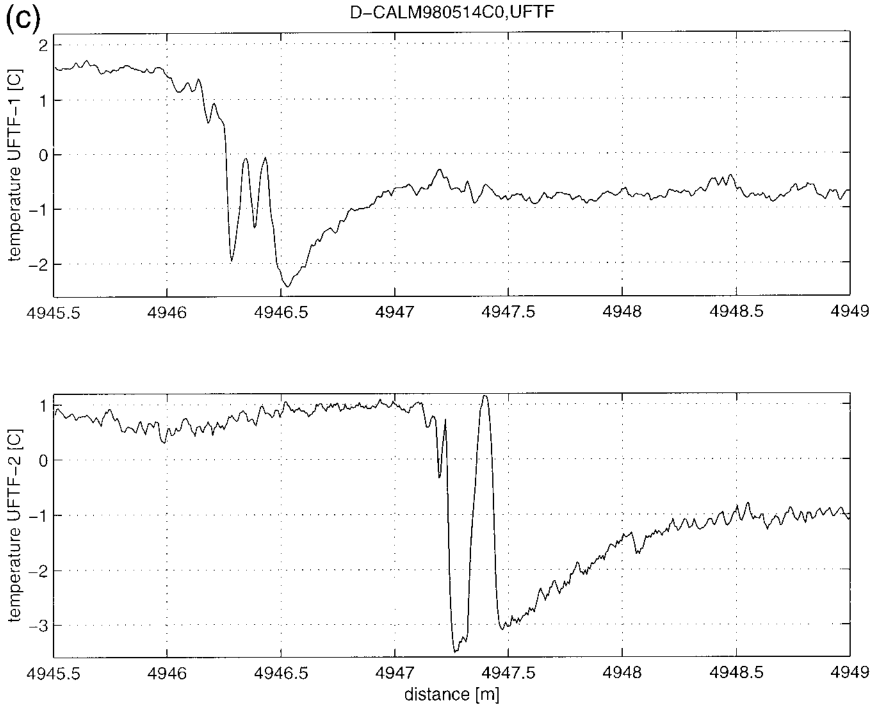

FIG. 9. (*Continued*)

stable. There are also some differences in performance between individual sensors, resulting from manufacturing technology that, as mentioned, is not fully standardized. Therefore, as already noticed, the recovery factor for this device may be difficult to determine. It seems that in its present shape UFT-F should be recommended for measuring temperature fluctuations with another slower thermometer as a reference, rather than for absolute measurements.

When interpreting the results of measurements with UFT-F, one should remember that the instrument measures the total rather than the static air temperature, and that in a turbulent atmosphere some fluctuations of temperature visible in the record may in fact reflect fluctuations of local airspeed. Rough estimates show that this may become a considerable problem at airspeeds over 100 m s^{-1}, and thus use of UFT-F at such airspeeds is not recommended or must be treated with greater caution. A solution to this problem may be to place a small, fast-response Pitot tube close to the sensor, but this yields a number of considerable technical problems (e.g., clogging by water in clouds) and has not been tried yet. A rough idea about the fluctuations of airspeed can be inferred from records of suction in Venturi nozzle. This has been tried in a few recent flights with certain limited success, but some improvements would be still needed. At present, limitation of the airspeed and careful consideration of whether particular features of the temperature record can be attributed to velocity fluctuations seem to be the most effective approach.

The present experience shows that the lifetime of the delicate sensing wire is very variable; some of the sensors survived several hours of flights and tests while some others broke fairly early, sometimes without any evident reason. Particularly dangerous is taxiing, during which the vane, stopped by the bumper, may become deflected relative to the wind, and various objects like sand grains or insects may be blown onto the wire, unprotected in that moment. Thus, use of at least two sensors whenever possible is recommended.

Another problem with use of UFT-F, particularly on large aircraft where long cables have to be used, are disturbances from various aircraft installations that generate electromagnetic noise. In the case of slower instruments some of the disturbances can be simply filtered out, but with UFT-F, which is often supposed to work in their range, they may sometimes surpass the noise of aerodynamic origin. This requires unusual care with respect to positioning and shielding the cables connecting the UFT-F to the recording system. The authors encountered this problem during some flights made with UFT-F on NCAR C-130Q aircraft in frames of the Wild Fire Experiment (August–September 1998) where such high-frequency electromagnetic disturbances generated by the aircraft electric installation in long and insufficiently shielded cables permitted digital recording with only a relatively low sampling rate of 200 Hz. One possible solution to this problem seems to be digitalization of the signal close to the sensor. Such a system is now under development.

The UFT-F sensor presented in this paper is a new member of the UFT family, designed for use on a plat-

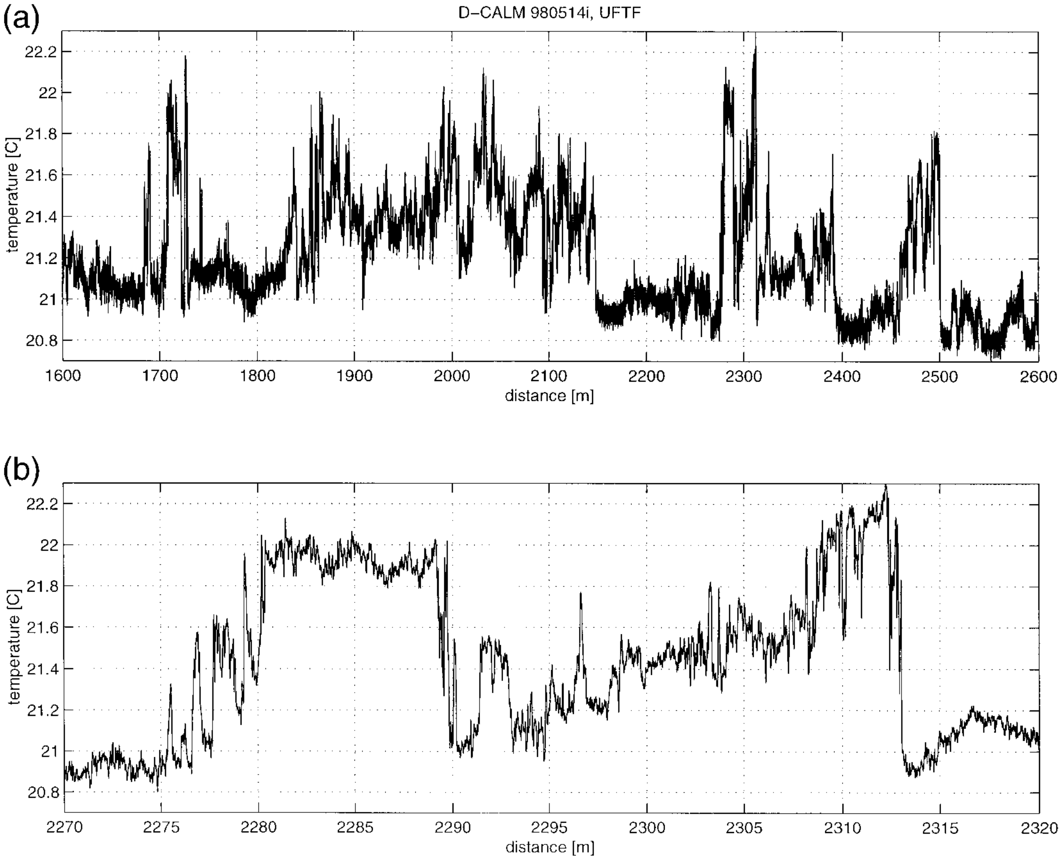

FIG. 10. Temperature fluctuations recorded with the UFT-F sensor on a 2-km pass 10 m above the airfield runway in convective weather. (a) 1-km fragment of the record. (b) Expanded segment of (a). (c) Power spectrum of the record; −5/3 slope plotted as a reference. Note the spikes at 400 Hz (frequencies of the aircraft AC network). For frequencies above 1500 Hz, influence of the signal low-pass filter is visible. The cleaner appearance than in Fig. 8 results from averaging over a longer time interval and from the fact that the record was taken shortly before landing, when some electrically noisy equipment had already been switched off.

form with an airspeed typical to most of the research aircraft presently used in cloud or boundary layer research. The UFTs are still under development, with respect to both their performance and modifications aimed at broadening the range of its applications. Construction of a specialized unit integrated with a five-hole turbulence probe for improved measurements of turbulent fluxes is being considered. With its time constant of the order 10^{-4} s it may take full advantage of very short response times of pressure transducers. In order to test the performance of UFT-F in boundary layer studies, the instrument has been flown about 10 m over the runway in convective weather. A fragment of the record from this flight as well as its spectrum are presented in Fig. 10, showing the effectiveness of UFT-F in reproducing a wide range of temperature fluctuations within a convective surface layer. Another member of the UFT family, the UFT-D (D for de-iced), a version with electrically heated selected parts, designed for measurements in supercooled clouds, is described in the next section.

5. Construction of the UFT-D

From the very beginning it was clear that the solution for adapting UFT-F to work in supercooled clouds is electric heating of all icing-sensitive parts of the sensor and its support. In principle this simple idea soon proved to be far from easy in technical realization; in particular, it was found that no commercially available anti-icing devices are suitable for this purpose. It was decided that the sensor must be redesigned in such a way that most of its parts must become electric heaters by themselves. This forced a change in the entire design of its mechanical structure, which is described in more detail below. It was also decided that UFT-D will be adapted to mount in a typical PMS container, available on most larger research aircraft, and its heating system will be supplied by 28 V DC rather than higher voltage AC (220 V/50 Hz, 110 V/60 Hz, or 110 V/400 Hz, depending on type of research aircraft), in order to avoid problems with contamination of the signal (recorded usually with a high sampling rate of up to 10 kHz or even more) by 50-, 60-, or 400-Hz noise.

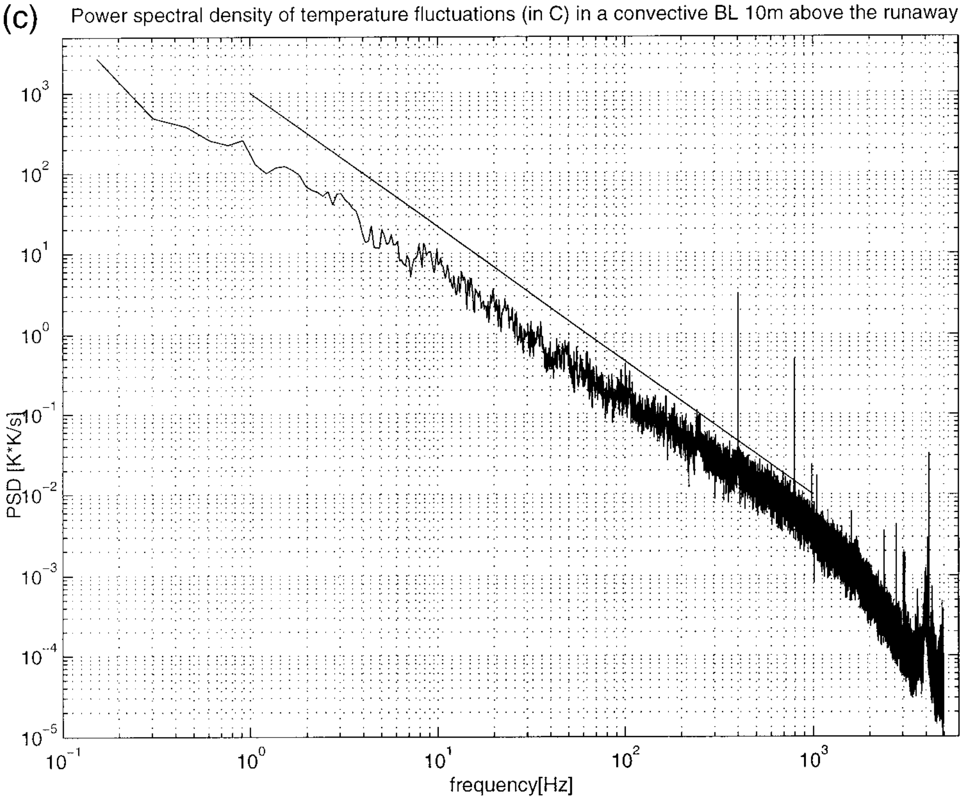

FIG. 10. (*Continued*)

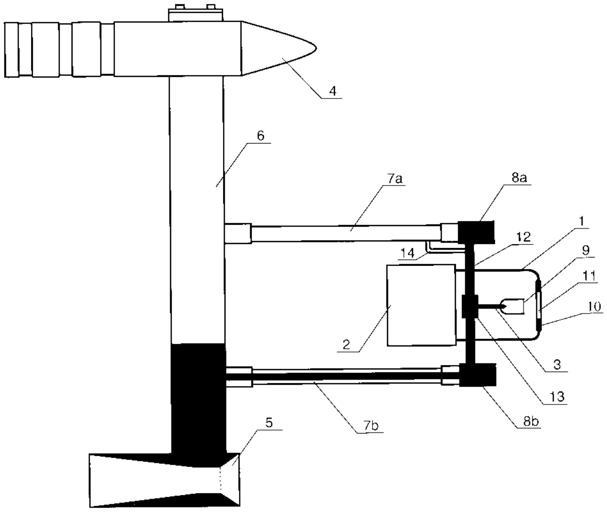

FIG. 11. Schematic view of UFT-D with heated parts marked in black. The labeled parts are (1) sensor frame, (2) vane, (3) sensor fork, (4) connecting head, (5) Venturi nozzle, (6) main vertical column, (7a,b) horizontal tubes, with a heated pneumatic duct inside 7b, (8a,b) tips with ball bearings, (9) sensing wire, (10) antidroplet protecting rod, (11) suction slots, (12) sensor shaft, (13) rotatable ring, and (14) flexible connecting wires.

Two prototype units of UFT-D were built at Warsaw University with financial support of Canadian Atmospheric Environment Service (AES) and tested during the Third Canadian Freezing Drizzle Experiment in January and February 1998. Because of technical limitations on the Convair 580 aircraft in which they were to be installed, the available current was limited to 7.5 A, which permitted heating with total power up to 210 W (in fact, even less because of losses on supply cables). First flights yielded results that proved that the general design of UFT-D is basically correct. The heating system was not introducing intolerable disturbances into measurement of air temperature and at least in some flights measurements from supercooled clouds were successfully collected. Nevertheless, the need for certain improvements in mechanical construction, particularly reduction of friction in the bearings system, became evident. Also, some redistribution of heating appeared necessary; certain parts required more effective de-icing, while others could be left without heating with no adverse effects from icing for the measurement process. After suitable modifications, most of these problems disappeared or were reduced to a tolerable level.

A schematic view of the UFT-D is shown in Fig. 11, while a photographic image is presented in Fig. 12. The instrument consists of the main supporting frame (elements 4–8 in Fig. 1) and the proper sensor with its shaft

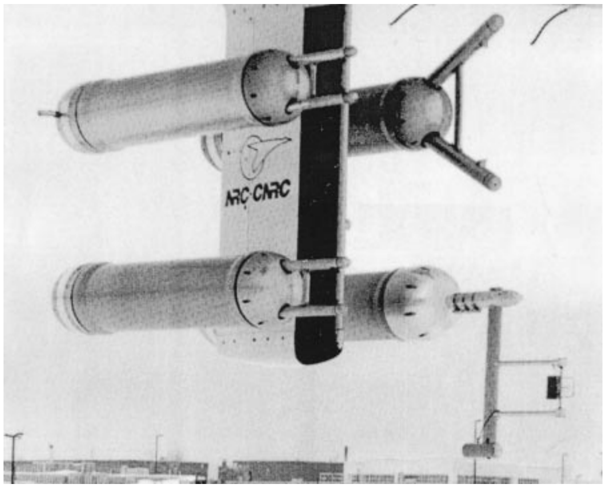

FIG. 12. UFT-D mounted in the lower-left-hand PMS container on the Convair 580 of the Canadian AES.

(12), frame (1), vane (2), and sensing element (3). At its upper end the supporting frame has a connecting head (4) for attaching the instrument to the PMS container inside of which the electronics are located. Construction of the head permits attaching and detaching of the instrument in a few minutes even in open air. Fixed at the lower end of the frame is a big Venturi nozzle (5), which creates the suction necessary for the instrument to work correctly.

The vertical column (6) of the supporting frame is made of a symmetric, airfoil-shaped, hollow duraluminum rod; it is 315 mm long and 40 mm wide with 17-mm camber and 1-mm-thick walls. Two horizontal aluminum tubes (7a,b) 195 mm long and 12 mm thick are ended with aluminum tips (8a,b) containing ball bearings of the sensor's shaft (12). The upper tube contains heater and signal cables; the lower one contains the heater cables and pneumatic duct connecting the Venturi nozzle (5) with the sensor.

The principal idea of the sensor design is the same as that of UFT-F, described in preceding sections. A 5-mm-long and 2.5-μm-thick platinum-coated tungsten thermoresistive wire (9), forming a branch of a Wheatstone bridge, is the principal temperature-sensing element. It is located on a small forklike support (3), 6.5 mm behind a vertical, airfoil-shaped rod (10), identical to that in UFT-F, protecting it against the impact of cloud droplets and other objects that might damage the wire. The rod (which is a part of the sensor frame) is hollow and has two slots (11) just behind the camber. Through these slots, suction from the Venturi nozzle (5) removes the water collecting on the rod and damps the eddies forming in its wake. During flying in supercooled clouds the rod is electrically heated in order to prevent icing. The main mechanical difference between UFT-D and UFT-F is that while in the latter the proper sensor with its frame and vane forms an integrated system with the support of the sensing wire (but not with the main supporting frame), in UFT-D the frame and vane of the proper sensor are permanently integrated with the main supporting frame, while the sensing wire support in the form of a small fork is removable. In case of damage to the wire in the UFT-F, the whole unit including the frame and vane has to be replaced, while in UFT-D only the fork with the wire is exchanged. This construction permitted the design of a relatively simple system of electric heating of all icing-sensitive parts: the shaft with its bearing system, the frame with the protective rod, the channel of water removal with the big Venturi nozzle, and the small fork with sensing wire. In this design the shaft (12) is made of a hollow fiberglass pipe, of which the central and lower parts serve as a duct for air-sucking and as a water removal system. It is plated with 0.2-mm-thick stainless surgical steel; the plating has a complex design (in order to ensure correct electric resistance) and serves as an electric heater. In contrast to the one point ball bearing in UFT-F, the shaft turns on two well-fixed ball bearings, which nest located in the tips (8a,b) filled with heat conducting silicone grease are also electrically heated. The frame (1) with the protective rod is made of one 1.8-mm-thick, suitably deformed stainless surgical steel tube with a wall thickness of 0.2 mm and is electrically heated by a current flowing directly through it. A Venturi nozzle (5) (95 mm long, with a 35-mm outer diameter, 31-mm inlet/outlet diameter, and 15-mm nozzle diameter) is embedded in a glycol bath, which is also electrically heated. The water collecting on the rod (10) is sucked off of it through the slots (11), hollow frame (1), hollow shaft (12), and pneumatic duct connecting it with the Venturi nozzle (5). A rotatable connector between the shaft and the duct is placed in the lower tip (8b) and sealed with silicon grease. The pneumatic duct consists partly of a stainless steel tube heated directly by an electric current flowing through it, hidden inside aluminum tube (7b), and partly of a soft, plastic tube embedded in the heated glycol bath that fills the the lower part of the column (6) and Venturi nozzle (5). The small ''sensor fork'' (3) is heated by a loop of 1.27 mm (0.05 in.) Teflon insulated constantan wire, placed inside the ''handle'' of the fork. The fork is connected with the shaft (12) by means of a ring (13) that can rotate around the shaft in a range of ±6°, in order to facilitate exchange of this element when needed. The handle of the fork contains 0.3-mm-thick copper signal cables in Teflon insulation that enter the fork ''dents'' made of 0.8-mm stainless steel tubes. The tips of these cables serve as fixing points for the sensing wire (9). The handle is filled with heat- and electricity-conducting, metalized epoxy resin. This fixes mechanically the heating and signal cables and shields them electrically each from the other, preventing induction of false signals by possible mechanical vibration of the cables. A flat, 3 mm × 40 mm × 53 mm hollow vane (2) made of stiff plastic foil contains in its front part points to which the signal and heating cables from the sensor fork can be soldered, becoming connected to the signal and heating networks of the system. From these points the signal is transmitted to the electronics box inside the PMS container by means of a three-line, double-shielded cable, which enters the vane through the upper part of the shaft (12) and the upper tip (8a).

As follows from the above description, the heating system consists of the following heated elements, marked black in Fig. 11: the sensor frame (1) with protecting rod (10), the sensor fork (3), the sensor shaft (12) with the ring (13), the tips with bearings (8a,b), the pneumatic/water removing duct inside the tube (7b), and the glycol bath that fills the lower part of the column (6) and the Venturi nozzle (5). The vane (2) remains unheated; it was expected that the relatively thick heated shaft (12) in front of it would protect it sufficiently against icing, while heating this part would considerably complicate its design. Test flights confirmed the correctness of this approach. All heating elements are connected in series, except the sensor fork (3), which is connected parallel to the sensor frame (1), consuming about one-tenth of its electric power. The sensor frame, shaft, and fork forming the rotatable part of the instrument are electrically connected to the remaining parts of the heating system by means of two thin, flexible, Teflon insulated copper wires (14). These wires are heated by the current flowing through them effectively enough to protect them against icing. A small mechanical limiter hidden in the upper tip (8a) limits the turning angle of the shaft (12), preventing the wires (14) from twisting. Total resistance of the rotatable part is nominally 1.1 Ω at 0°C, with a few percent tolerance, depending on manufacturing details. The temperature excess to which its elements can be heated depends on the current available from the aircraft's 28-V DC network and ventilation conditions, which in turn depend mostly on the atmospheric pressure and airspeed. The tips (8a,b) as well as the glycol bath around the lower part of the pneumatic duct and Venturi nozzle are heated by means of heaters made of twisted, Teflon-insulated, 0.7-mm-thick constantan wire with specific resistance of about 1 Ω m^{-1}. Its total length (and thus resistance) must be customized to the particular aircraft in use, in order to keep the current below the maximum value permitted by the design of its 28-V DC network. In the case of flights on Canadian AES Convair 580 aircraft this was about 7.5 A. At cruising airspeeds of up to 100 m s^{-1} this permitted successful measurements in low-level clouds supercooled down to at least -8°C with liquid water content up to 2 g m^{-3}. It is important to ensure adequate heating of the Venturi nozzle, which is additionally chilled by adiabatic cooling within its throat.

When designing the UFT-D, particular attention was paid to the danger of possible induction of false signals by mechanical vibrations of the signal cables with respect to the heating cables, through which a relatively strong electric current is running, generating a strong magnetic field. In order to avoid these effects the cables are carefully twisted, mechanically fixed, and shielded wherever possible. On a large part of its length the signal cable has an additional shield made of a ferromagnetic material. These measures seem adequate, since no signs of such disturbances were encountered during test flights.

The electronics for UFT-D forms a separate part and is the same as that used for UFT and UFT-F. Basically, it consists of a Wheatstone bridge with the sensing wire in one branch, supplied by a stabilized DC voltage (usually this was 10 V but other options are also possible), operational amplifier, and some auxiliary elements such as power suppliers, switches, filters, etc. The electronics is located inside the PMS container and carefully shielded against external electromagnetic disturbances by means of a double box made of zinc-plated magnetic steel. It provides an outgoing analog signal adjusted to the requirements of the onboard recording system; usually its strength corresponded to about 65 mV K^{-1}. Electronics also includes a differential pressure transducer connected with the Venturi nozzle with an additional pneumatic line. It permits checking whether the suction is correct and operates a safety relay for switching off the heating system if there is inadequate ventilation.

In a case of damage to the sensing wire the whole small sensor fork has to be replaced with a new one. This can be done with a few simple, standard tools in about 30 min, but requires at least basic workshop conditions. Particularly, fixing the fork in correct position and sealing all possible microleakages from the pneumatic duct inside the shaft, which might appear during the replacement operation, needs some care, precision, and skill. Since in operational exploitation of the instrument there may not be adequate time or conditions for such a replacement, at least two complete UFT-Ds should be available. If the electronics remains good so that the PMS container need not be opened, exchange of the whole instrument is a simple operation and can be made with a screwdriver in a few minutes, even in the open air, allowing the replacement of the damaged fork to be done later. Replacement of a damaged wire on the fork is more complicated; it needs special instrumentation and good laboratory conditions, and takes a skilled technician more than an hour of work. If there is no easy access to a suitable laboratory, preparing an adequate stock of spare sensor forks in advance is desirable, because damage to the delicate wire may happen from time to time.

As in the case of UFT-F, reliable calibration for absolute temperature measurements is difficult and uncertain, and thus this device should be used rather for fluctuation measurements only. Since most research aircraft have separate, well-calibrated, slow response thermometric units like, for example, standard Rosemount aircraft thermometers, in-flight comparison with such instruments permits determination of sensitivity of particular UFT-Ds with satisfactory accuracy for that ap-

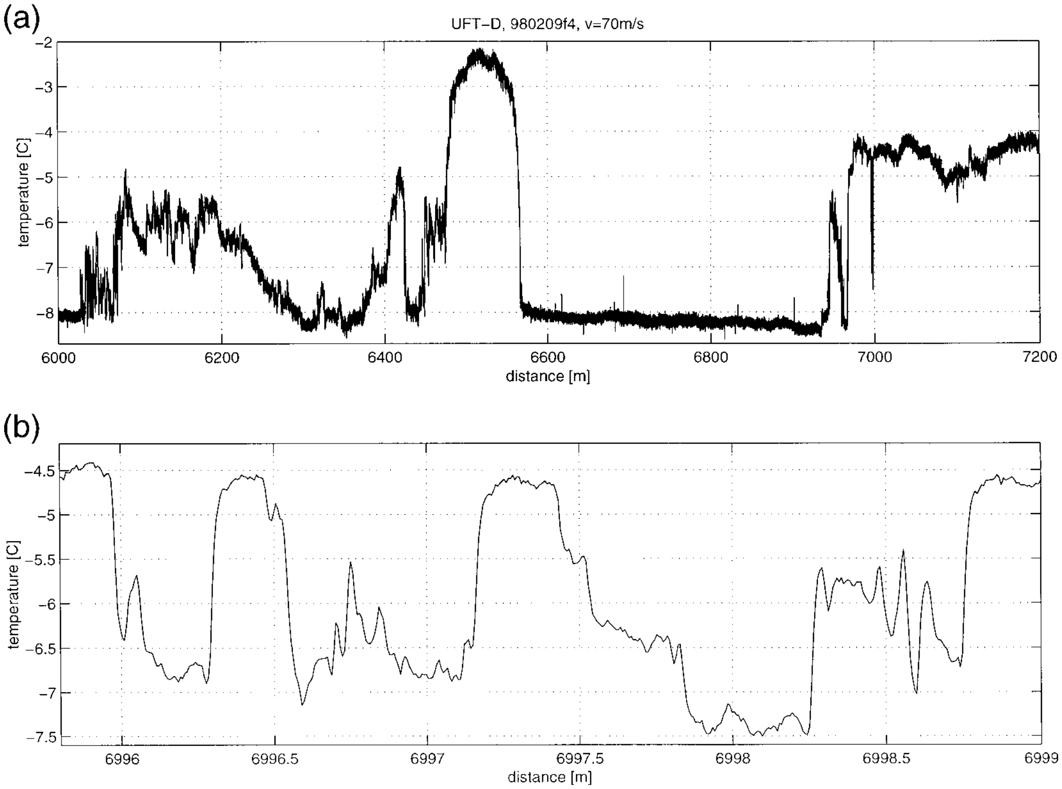

FIG. 13. Fragment of a UFT-D record taken during the CFDE3, with 10-kHz sampling rate, showing rapid variations of temperature over a few centimeters in distance. Airspeed is 70 m s^{-1}, and distance is measured from the beginning of the record. The temperature scale is according to the reference Rosemount thermometer. (a) General view. (b) Selected fragment of (a), with expanded distance scale.

plication, as well as establishment of a reference temperature scale.

6. Test flight results and following conclusions

As mentioned in the introduction, the UFT-D has been tested in a few flights during the CFDE3 in January and February 1998.[1] The instrument was installed on the Convair 580 research aircraft, belonging to the Canadian AES, in one of the outer left-wing PMS containers (Fig. 12). A signal was recorded on the central recording unit with 100-Hz sampling frequency during the whole flight, but in order to take full advantage of the speed of the sensor selected fragments were additionally recorded with a 10-kHz rate after conditioning by a 3-kHz, second-order Butterworth low-pass filter. This additional recording has been performed on a Toshiba 440 notebook, by means of the IOTech Daq 216 Card A/D converter, under DAQVIEW data logging software. The software permitted permanent viewing of grab-sampled 10-kHz signal, but only short selected fragments lasting a few minutes could be recorded due to limited capacity of the available disk space and memory buffer. Thus not all important observations of the behavior of UFT-D are documented in the form of a fast-response record. The instrument has been used for temperature fluctuation measurements, with one of the Rosemount thermometers installed on the aircraft as a reference for determining the temperature scale in each individual flight. Sensitivity of the instrument has been determined in this way with about 5% accuracy; it varied between 64 and 70 m V K^{-1}, depending on the particular fork in use. In Fig. 13 a fragment of a record made in a supercooled cloud is presented. Notice sharp jumps of temperature over centimeter distances, similar to those observed in warm clouds by means of UFT and UFT-F and described by Haman and Malinowski (1996a,b) and Haman et al. (1997). An example of such a record is also presented in the paper by Korolev and Isaac (2000). Tests with switching the heating on and off during flights in clear air (Fig. 14) proved that although the overheating of the protecting rod over ambient temperature was estimated as more than 10 K, it shifts the temperature record not more than 0.3 K. This

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[1] UFT-D has been used also during the Alliance Icing Research Study (AIRS) in Canada in winter 1999/2000 in a similar configuration to that during the CFDE3, but most AIRS data were not fully processed at the time of submission of the present paper. Figure 14 makes use of data from one of these AIRS flights.

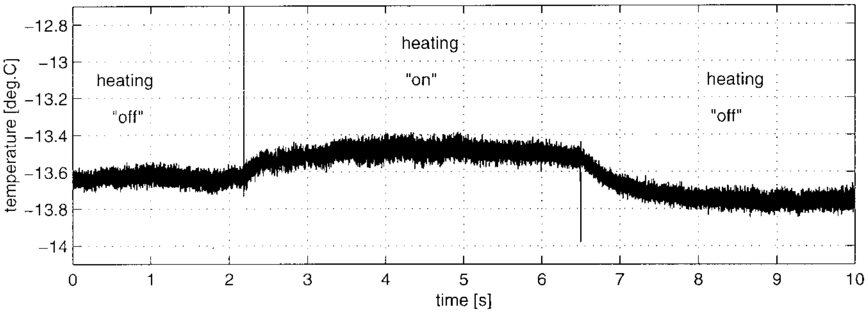

FIG. 14. Fragment of temperature record made with UFT-D outside the cloud, with heating switched off, on, and off. Pressure is 576 hPa, and airspeed is 110 m s^{-1}. Slight asymmetry of the record follows from variation of temperature along the flight path.

shift can be treated as a constant correction (unimportant for fluctuation measurements). Additionally, its value shows that the thermal influence of the protective rod on the measurement is even smaller than that found for UFT-F in the wind tunnel tests presented in Fig. 5. It was also noticed that switching the heating on does not increase significantly the level of thermal noise. However, this was found to be true only for flights at altitudes of up to 2–4 km above sea level with airspeeds of about 100 m s^{-1}. During one flight made at a altitude of 5–6 km with a speed of about 150 m s^{-1} such tests showed considerable increase of the noise when heating was on. The reason for such behavior is unclear; probably the regime of heat exchange at higher airspeeds and lower air densities or pressures becomes different.

In its initial form, the UFT-D prototype had a number of minor constructional and manufacturing faults, resulting in destruction of the sensing wire after a few minutes of service. These faults were successively removed as they were identified, so that survival of the sensor over the whole flight in which icing conditions were encountered was finally achieved. However, the problem with vulnerability to big ice crystals remains open. It has been identified due to the fact that the Lawson's cloud particle camera imager (Lawson 1997), permitting online observation of the nature and size of encountered cloud particles, was on board. The wire survived successfully for more than 20 min of a flight in cirrus clouds with crystals smaller than about 200 μm, but broke almost instantly when the aircraft entered a region of bigger ice particles. Presumably, big asymmetric crystals struck by the protective rod may turn, enter the protected area, and destroy the wire. Efforts are under way to endow UFT-D with some preprotective devices that are hoped to prevent such events, but this appears technically difficult, and work on this solution is as yet uncomplete. Thus, at present, usefulness of UFT-D is limited to clouds not containing big ice crystals or graupel.

7. Final conclusions

The aircraft immersion thermometers UFT-F and UFT-D described in the present paper are new members of the family of ultrafast airborne thermometers (UFTs). They evolved from the earlier version, designed for use on slow airplanes or gliders (Haman et al. 1997), but due to a new design of the protection against cloud droplets they permit measurements of total temperature in clouds and cloud-free atmosphere, with spatial resolution going down to millimeters at airspeeds of up to 100 m s^{-1}. The time constant of the bare sensor is of the order 10^{-4} s, and thermal inertia of the antidroplet protection (time constant of the order 10^{-1} s) combines with that of the sensor with only a small percentage. Temperature resolution of these instruments is limited mostly by the noise of instrumental origin, the amplitude of which is about 0.2 K, peak to peak. So far, in a few flights in clouds made with the recent versions of UFT-F, no evident signs of wetting have been noticed, which suggests that its antidroplet protection is effective; however, the statistics are still too limited to state this with a higher degree of certainty. A longer period of in-flight exploitation of this instrument is necessary to formulate a more definite conclusion. Short experience with the de-iced version UFT-D shows that ultrafast measurements of temperature are also possible in supercooled clouds.

UFT-F and UFT-D are not free from certain drawbacks and unsolved problems. For instance, the present manufacturing process is not fully standardized, which causes differences in performance between various individual sensors, particularly UFT-Fs. In principle this could be overcome, but the corresponding cost would presumably be prohibitive. For similar reasons, stable calibration of the sensors and universal determination of their recovery factor are difficult to achieve, which makes them inappropriate for absolute measurements of static temperature and limits their use mostly to measurements of temperature variations.

Extension of operational use of UFT-F and UFT-D to a wider range of aircraft and meteorological conditions requires finding solutions to at least the three following problems:

1) sensitivity to electronic disturbances,

2) discrimination between static and dynamic variations of temperature at higher airspeeds, and
3) vulnerability of the sensing element in UFT-D to big ice crystals.

The first is going to be solved by digitalization of the signal close to the sensor. The second one is more difficult to solve; perhaps redesigning the pneumatic (suction) system and recording the suction in the Venturi nozzle as a measure of air velocity may be a correct approach. The third problem is probably the most difficult one. Some concepts of solving it by introducing an additional protective rod of a different shape are now in the early stages of development and testing.

Nevertheless, even with all of those drawbacks (some of which hopefully will be eliminated in the course of the sensor's further development and improvement) UFT-F, as well as other members of the developing UFT family, creates new possibilities for in situ investigations of ultra-small-scale temperature inhomogeneities in clouds as well as in cloud-free air. This may essentially help in solving many questions connected with the dynamics and thermodynamics of mixing and other small-scale atmospheric processes.

In conclusion, it can be stated that aircraft thermometers with a time constant of an order 10^{-4} s, permitting spatial resolution down to a centimeter scale and able to work (with some limitations) in both warm and supercooled water clouds, are available. Although until now there have been only limited possibilities for testing their performance, the preliminary results are promising.

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