The LMD Frost Point Hygrometer

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The "Laboratoire de Meteorologie Dynamique", LMD, took part in various programs which imply in-situ measurement of the water vapor content in the middle and lower stratosphere and high troposphere.
Considering how difficult it is to make "in situ" measurement of the weak contents of water vapor in the stratosphere, a balloon-borne instrument was developed at LMD. **The first flight onboard Open Stratospheric Balloons** (BSO) took place in **1986** from the balloon launching station of CNES (Centre National d'Etudes Spatiales) in Aire sur l'Adour (Ovarlez J et al., 1987).
The aim was to develop an instrument to be carried by long duration balloons, the Infra-Red Montgolfiere (MIR), and **the first flights of the LMD hygrometer onboard MIR** took place in **1988** (Ovarlez J, 1991). Then, this hygrometer was modified in order to be carried **onboard aircraft in 1994** (Ovarlez J et al. 1996).

1. PROBLEM TO BE SOLVED

The vertical distribution of the atmospheric water vapor content, although very irregular in the troposphere, is characterized by the prevalence of a large decrease with altitude up to the tropopause level.
In the stratosphere the molar fraction of water vapor (usually indicated "volume mixing ratio") reaches few ppmv (part per million in volume), which correspond to frost-point temperatures ranging between -75°C and -95°C, for an atmospheric pressure ranging between 200 hPa. and 10 hPa., and an air temperature being between -40°C and -90°C. The weak water vapor contents, and the surrounding atmospheric conditions make in-situ measurements difficult. In the stratosphere, it is not sufficient to have an instrument able to measure these contents taking into account the environmental conditions, as it is necessary to take many precautions to avoid pollution from the balloon and from the payload.
Two design of balloons, implemented by the CNES, were used: Open Stratospheric Balloons (BSO), and Infra-red Montgolfieres (MIR). The BSO allows to carry out a vertical profile for a flight duration of a few hours and can carry heavy payloads, up to several hundred kilograms depending on the volume of the balloon. The MIR is a hot air balloon, like a montgolfiere, volume 36000 m3, and whose flight level depends on the collected radiation. During the night time, the balloon is heated by the terrestrial infra-red radiation; during day time, the additional heat provided by the sun induces the ascent of the balloon. The flight altitude of the MIR varies on average between 20 km during the day and 30 km during the night; the flight duration of these balloons can be more than one month. Their fall down is

due to their flight over significant cloudy area, during the night, which cut the balloon from its source of thermal energy, namely the ground. The payload is about 50 kg. Within the framework of the LMD campaigns devoted to water vapor measurements (program AMETHYSTE) the localization and the data collection were provided by the ARGOS system onboard satellite.
In the troposphere, it is necessary to have an instrument having a wide range of measurement as the water vapor mixing ratio vary between some ppmv and a few thousands of ppmv. In that part of the atmosphere, an aircraft was used: the German research aircraft, a Falcon, implemented by the DLR (Deutsches Zentrum für Luft und Raumfart), and whose altitude can reach 13 km.

2. INSTRUMENTAL CHOICES

2.1 The hygrometer using a thermoelectric cooler

To solve the various constraints occurring from the use of short and long duration balloons, a chilled mirror frost-point hygrometer using a thermoelectric Peltier device was built at LMD. The chilled mirror technique is simple and well known. The occurrence of dew or white frost on a cooled mirror is detected in an optical way. The temperature of the mirror is maintained at the temperature of condensation by a feedback loop controlling the cooling and the heating of the mirror. This temperature, the dew or frost point temperature is directly connected to the partial pressure of water vapor that characterizes the water vapor content of the atmosphere. The simultaneous measurement of the air pressure and air temperature allows the determination of the mixing ratio and of the relative humidity (Annex I).

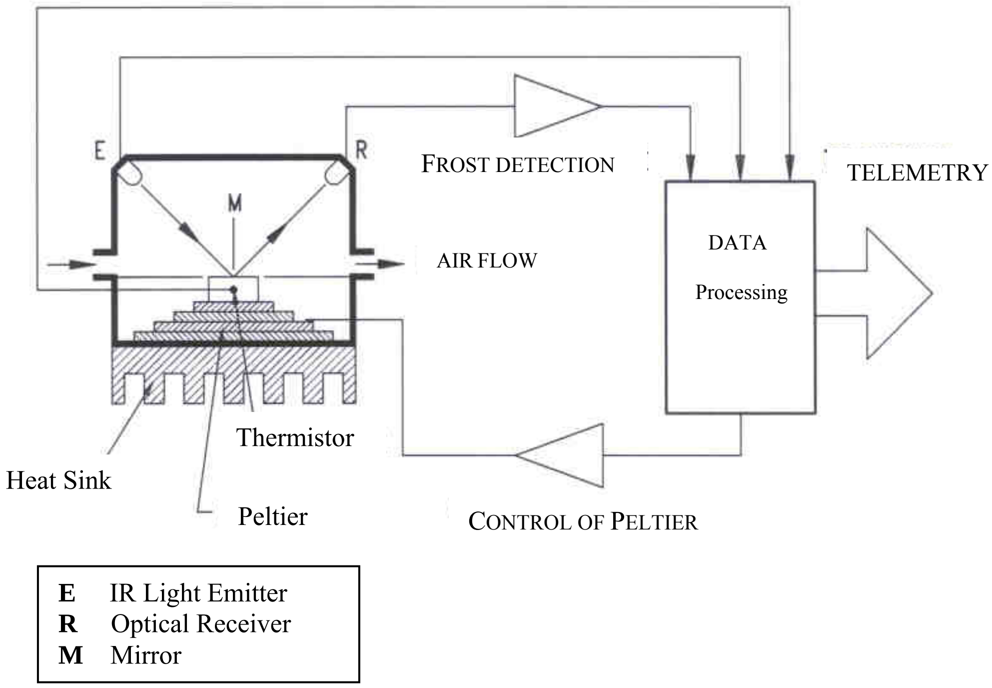


Figure 1 : Operating diagram of the frost point hygrometer

In the LMD instrument, the control of the temperature of the mirror is provided by a 4 stages thermoelectric module. The gilded copper mirror is directly stuck on the cold side of the thermoelectric module, and the temperature of the mirror is measured by a thermistor

embedded in the mirror, very near to its surface. A microprocessor makes the control of the drifts of the optical system and of the electronic components, their transfer and data processing towards the telemetry, as well as the regulation and control of the temperature of the mirror. The program, run by the microprocessor, and which controls the temperature of the mirror, uses more fuzzy logic than traditional proportional control loop. This is because, at the low frost-points to be measured, the way the white frost deposits on the mirror is not always reproducible, even under clearly defined conditions.
The thermistor embedded in the mirror is calibrated with respect to a platinum sensor associated to a multimeter both connected to the National Standards. In the same way, the air pressure sensor, essential to accurate mixing ratio determination, is calibrated with a transfer standard connected to the National Standards.
By using a Peltier thermoelectric module, we have an autonomous instrument which can be used on long duration balloon (MIR). However there are some limitations: the cooling efficiency of a thermoelectric module is strongly dependent on the temperature of the heat sink which is connected to the "hot side" of the module. As example, it is necessary to have -40°C on the hot side to reach -95°C on the mirror. One understands easily that measurements during the day are generally impossible, the instrument being strongly heated by solar radiation. On the other hand, during the night the heat sink is almost at the surrounding air temperature, which is generally between -40°C and -80°C according to the altitude of the balloon, and the cooling efficiency of the Peltier becomes sufficient to reach the low frost-points. However, for the MIR flights, it was necessary to develop, with the assistance of the CNES, a special heat sink looking upward to the sky, so that the instrument is cooled quickly when the sun lays down, i.e. when the MIR begins to go down towards its ceiling altitude of nighttime. The same kind of heat sink, a flat metal plate, was also used for measurements from BSO.

The instrument, with a Peltier module, flew onboard BSO until 1993 and onboard MIR until 1996. It was no more used after 1996, as a consequence of the end of the AMETHYSTE program (AMETHYSTE devoted to the water vapor measurements in the equatorial stratosphere by using the frost point hygrometer onboard MIR)

2.2 The hygrometer using cryogenic cooling

From 1994, for the BSO and aircraft flights, the Peltier module was replaced by a cryogenic cooling system. This cooling system was selected so that the hygrometer could be used onboard aircraft, as the temperatures inside the aircraft are not low enough to have the necessary cooling efficiency of the Peltier module. In the new configuration of the hygrometer the mirror is stuck on a copper rode plunging in liquid nitrogen enclosed in a dewar container, especially adapted, which provides a permanent cooling. The control of the mirror temperature is made through the adjustment of the heating of the mirror which is provided by a resistive wire rolled up around the copper rode. The use of cryogenic cooling made it possible to decrease considerably the response time of the hygrometer, compared to the Peltier instrument. In addition, in the program run by the microprocessor, the algorithms for the control of the mirror temperature were set to take into account the different ranges for the frost point temperatures to be measured from aircraft on one hand, and from BSO on the other hand. Let us note that the optical system and the associated mechanical structure remain the same ones as for the Peltier instrument, as shown on the illustrations of annex IV. The mirror and the embedded thermistor are, them also, similar.

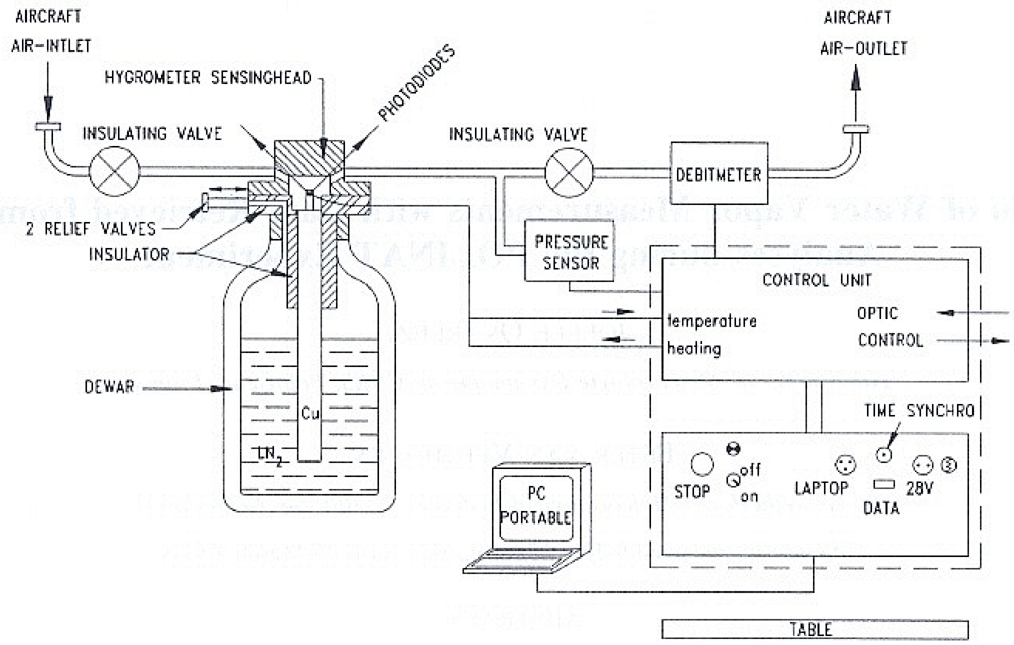


Figure 2: Diagram of the aircraft borne hygrometer

The development of the described instruments was made easier by the use of the LMD calibration system for hygrometers which allows the generation of environmental conditions, encountered in the stratosphere as well as in the middle and upper troposphere, for temperature, pressure, and moisture together (Ovarlez J, 1984, and annex I). This tool has been essential, particularly for the development of the program which controls the temperature of the mirror around the frost point through the microprocessor. In fact, this required hours and hours of simulations under different conditions. The hygrometers calibration system and the calibration facilities for temperature and pressure are the guarantee of reliable measurements.

3. SUMMARY

The instruments

The instruments developed at LMD are frost point hygrometers using chilled mirror technique and optical detection of the white frost on the mirror for:
• The long duration balloons (Infra Reds Montgolfieres, MIR)
• The Open Stratospheric Balloons (BSO)
• The research aircraft (since 1994)

2 systems for the cooling of the mirror are used:
• Cooling of the mirror by a thermoelectric module (Peltier) to have the autonomy necessary to the flights of long duration balloons (MIR).
This technique has been used for MIR flights until 1996, and also for BSO flights until 1993.
• Cryogenic Cooling for BSO and aircraft measurements from 1994

- These instruments allow direct measurement of the frost point temperature with an uncertainty 2 σ = 0.3C for the cryogenic hygrometer, and 0.5C for the Peltier hygrometer.
- Joint measurement of the atmospheric pressure and temperature are made (Paroscientific sensor for air pressure; microbead thermistor VEECO Victory engineering Co. for the air temperature from balloons, and operational Rosemount/Goodrich temperature sensor for the measurements from aircraft).

One can thus calculate the hygrometric parameters (cf. annex I). The volume mixing ratio is then obtained with an uncertainty 2 σ = 3 to 6 % for the cryogenic hygrometer and 10% for the Peltier hygrometer

• The first balloon flight took place in 1986, a BSO flight starting from Aire sur l'Adour
• The first experiment from aircraft took place in 1994

The research programs:
The LMD frost point hygrometer was used during many national and European research programs. The hygrometer payload, onboard balloons, is commonly known under the name of ELHYSA following an acronym used for the first research programs, as "Etude de L'Hygrométrie StrAtospherique". Then it was easy to keep this name as it is well known by our partners, particularly European partners.
Among the scientific programs the ELHYSA payload was associated to, there are:
- For MIR flights: AMETHYSTE (Application des Mir à l'ETude de l'HYgrométrie STratosphériquE) 1991, 1994.
- For BSO flights: CHEOPS (Chemistry of polar stratosphere) 1990; EASOE (European Arctic Stratospheric Ozone Experiment) 1991-92; TRAVERSE (Tracking vortex elements reaching southern Europe) 1993; SESAME (Second European Stratospheric arctic and mid latitude experiment) 1994-95; SABINE (Summer Arctic Balloon International Experiment) 1998; THESEO (Third European stratospheric experiment one ozone) 1999-2002; CIPA (Comprehensive investigation of polar stratospheric aerosols) 2000-02;

Satellite validation from SAGE II (1989-90), ILAS (1997), ODIN (2001) and ENVISAT (2003-04).
- The aircraft hygrometer took part in POLINAT I and POLINAT 2 (Pollution from aircraft in the North Atlantic flight corridor) 1994-95, 1997 and INCA (Inter hemispheric difference in cirrus properties from anthropogenic emissions) 2000.

In the Annex III there is the list of the publications referring to the results of the measurements of the water vapor during various campaigns.

The data base:
All the data from MIR and BSO experiments over the period 1988 - 2005, are public and are in the data base ETHER. To the water vapor measurements, are associated the air temperature and air pressure measurements, as well as the localization of the balloon (CNES data).
For the aircraft experiments, the data on ETHER include the measurements taken within the framework of POLINAT I and POLINAT 2.
The water vapor data from INCA are not in ETHER, because as measured in the occurrence of cirrus clouds, it requires the use of measurements of the other instruments, onboard the aircraft, to discriminate the presence or absence of cirrus. They are available in the base specific to INCA (http://www.pa.op.dlr.de/inca/)

ETHER:
http://ether.ipsl.jussieu.fr/
"Data/Services"
"select by experiment"
"Balloon-borne experiment " or "airborne experiment"
" ELHYSA"

"ELHYSA2" will comprise the data from the flights of the hygrometer obtained from October 2005

4. THE PARTICIPANTS

At LMD, many people contributed to the development of the instrument.
The main contributors are: Henri Ovarlez as Principle Technical Investigator, Joelle Ovarlez as Scientific Investigator, Jacques Capus, Jacques Crespin, Bertrand Gaubicher, and among the non permanent people, Eric Landais.
The mechanical and design department of LMD contributed, with more particularly Bernard Gillet and Olivier Bousquet.
The balloons were implemented by the CNES, and the aircraft by the DLR (Germany). We thank the operational balloon team at CNES, and particularly Pierre Malaterre for MIR flights, late Pierre Faucon for the success of all the balloon campaigns we took part with him, and Pierre Dedieu for meteorological support. We thank the operational team of DLR for the operation of the Falcon aircraft. We thank Ulrich Schumann and Hans Schlager (Institute fur Physik for atmosphäre, Oberpfafenhoffen, Germany) to have incited us to use the hygrometer on aircraft, as this enabled to improve the instrument considerably. The programs which allowed the development of the instrument and the participation in balloons and aircraft campaigns were financed by the BNM (Bureau National de Metrology), CNRS INSU, CNES, and the European Commission.

References

These are only the first publications on BSO, MIR, and aircraft measurements and on the calibration system. The whole bibliography is in annex II).

Ovarlez Joëlle, Un système pour l'étalonnage et étude d'hygromètres bas points de rosée, *Bulletin du BNM, 58, 51-55, 1984*

Ovarlez J., B. Brioit, J. Capus and H. Ovarlez, Développement et essais en vol ballon d'un hygromètre à point de rosée pour sondage de l'atmosphère, *Bulletin du BNM*, 69, 9-14, 1987

Ovarlez Joëlle, Stratospheric Water Vapor Measurement in the tropical Zone by means of a Frost-point Hygrometer on Board Long-Duration Balloons, *J. Geophys. Res., D8, 15,541-15,545,* 1991.

Ovarlez Joelle, Henri Ovarlez Rose-Marie Philippe and Eric Landais, Water vapour measurements during the POLINAT campaign, *Air Pollution Report N°58*, Office of Publication of CEC, Bruxelles, 1996.

ANNEX I: DETERMINATION OF THE HYGROMETRIC PARAMETERS

I GENERAL CASE

I-1) The hygrometer measures the frost point temperature.
It is the temperature to which the air is saturated with respect to the ice .
The measurement of this temperature allows to calculate the water vapor pressure in the air, e' , which one identifies to the vapor pressure in pure phase e (in the field of interest the factor f such than e' =f.e is 1 within 1/1000).
To determine the vapor e pressure, the OMM formulas (1984) are used - cf III -.
From e and the atmospheric pressure P, the volume mixing ratio is calculated [I-2)]
From e and the ambient temperature Ta, the relative humidity is calculated [I-3)]

I-2) The molar fraction of water vapor or "volume mixing ratio" xv = nv/(nv + na) is the ratio of the number of mole of water vapor (nv) to the total number of moles of the humid air (nv + na).
One shows: xv = e' /P = e/P ratio of the water vapor pressure, e , to the total pressure of the humid air, P.
It is without dimension. When expressed in 10^{-6}, the unit is the ppmv; often indicated by r

e is inferred from the measurement of the frost point temperature by the hygrometer. P is measured by the air pressure sensor onboard the hygrometer payload.

I-3) the relative humidity

$RHi = 100 \frac{e}{e_i(Ta)}$ Relative Humidity with respect to ice, in %

$RHw = 100 \frac{e}{e_w(Ta)}$ Relative Humidity with respect to the liquid phase, in %

e inferred from the measurement of the frost point temperature by the hygrometer.
e_i (Ta) et e_w (Ta) saturation vapor pressure respectively above ice and liquid water at the air température Ta (e, e_i et e_w calculated with the OMM or Sonntag formula –cf III)

II AIRCRAFT FLIGHTS

II-1) Frost point temperature and mixing ratio:
The frost point temperature, Tdh, measured by the hygrometer is a little different from the frost point temperature, Tde, of the air crossed by the aircraft. This is because of the difference between the pressure P_h at the hygrometer sensing head and the pressure P_e of the air outside the aircraft, induced by the air inlet * and the aircraft speed (cf figure 2).
On the other hand the volume mixing ratio, r , is maintained.

that is to say $r = \frac{e_h}{P_h} = \frac{e_e}{P_e}$

e_e saturation vapour pressure at Tde
P_e static air pressure
e_h saturation vapor pressure at Tdh (measured by the hygrometer)
P_h pressure at the hygrometer head.

the volume mixing ratio $r = \frac{e_h}{P_h}$ is inferred directly from measurements at the hygrometer.

** a forward facing Rosemount-Goodrich Modified temperature housing*

Determination of Tde:

$e_e = e_h\,[P_e/P_h] = r \cdot P_e$

OMM or Sonntag formula (cf III) cannot be used directly. Then we use an approximate formula to calculate Tde from from e_e (Marti et Mausberger, 1993) :

$$T = \frac{A}{\mathrm{Log}(10)e - B}$$

A = -2663.5 ± 0.8
B = 12.537 ± 0.011
e, saturation vapor pressure above ice at temperatute T ; *e in pascals; T in K*

In order to fit A and B, the hygrometer measurements from many aircraft flights have been used (POLINAT):
For RHi = 100,00% we should have Ta=Tde if the OMM formula (cf III), used to calculate RHi, and the Marti-Mausberger formula, used to calculate Tde, are strictly equivalent.
We keep the mean value for A, A= -2663.5, and fit B to have Ta= Tde, when the measurements give RHi = 100%
We found that B is a function of the frost point temperature :

$$B = 12.537 + [\,1.14\ 10^{-4}\,(T) - 4{,}47\ 10^{-4}]$$

With T = Tdh (*Here T is in C)*
Between -30 et -60C, the corrective factor for B is between -0.004 et -0.007 (which is in the range of the corrective factor from Marti and Mausberger).

II-2) <u>The relative humidity</u>:
The air temperature, Ta, from the aircraft instrumentation is needed.

$$RHi = 100\,\frac{e_e}{e_i(Ta)} = 100\,\frac{e_h}{e_i(Ta)}\cdot\frac{P_e}{P_h} = 100\ r\ \frac{Pe}{ei(Ta)} \quad \text{relative humidity/ice} \quad (\%)$$

$$RHw = 100\,\frac{e_e}{e_w(Ta)} = 100\,\frac{e_h}{e_w(Ta)}\cdot\frac{P_e}{P_h} = 100\ r\ \frac{Pe}{ew(Ta)} \quad \text{relative humidity/liquid phase} \quad (\%)$$

e_i (Ta) et e_w (Ta) saturation vapor pressure respectively above ice and above liquid water at temperature Ta

r volume mixing ratio inferred from the hygrometer measurements ($r = \frac{e_h}{P_h}$)

III <u>SATURATION VAPOR PRESSURE FORMULATION</u>

ew with respect to liquid water, and ei with respect to ice, at temperature T.

OMM Formulas (World Organization of Meteorology - WMO)

$$\begin{aligned}\mathrm{Log}\,(10)\,e_w = {} & 10{,}79574.(1-T_1/T) - 5{,}02800\ .\ \mathrm{Log}(10)[T/T_1] \\ & + 1{,}50475.\ 10^{-4}\,[1 - 10^{-8{,}2969\,(T/T1-1)}] \\ & + 0{,}42873\ .\ 10^{-3}\,[10^{\,4{,}76955\,(1-T1/T)} - 1] + 0{,}78614\end{aligned}$$

T_1 = 273,16 ; e_w in hPa, et T in K

$$\mathrm{Log}\,(10)\,e_i = -9{,}09685\left(\frac{T1}{T} - 1\right) - 3{,}56654\ \mathrm{Log}\,(10)\left[\frac{T1}{T}\right] + 0{,}87682\left[1 - \frac{T}{T1}\right] + 0{,}78614$$

T_1 = 273,16 ; e_i in hPa, et T in K

The European standards (AFNOR 1994) recommend the Sonntag (1990) formula

$$\ln(e) = AT^{-1} + B + C\,T + D\,T^2 + E\,\ln(T)$$

For ew, in the temperature range -100°C to +100°C:
A = -6096.9385, B = 21.2409642, C = -2.711193E-2, D = 1.673952E-5, E = 2.433502.
ew in Pa and T in K. [To have ew in hPa, replace 21.2409642 by 16,635794]

For ei, in the temperature range 0.01°C à -100°C :
A = -6024.5282, B = 29.32707, C = 1.0613868E-2, D = -1.3198825E-5, E = -0.49382577.
ei in Pa and T in K
[To have ei in hPa replace 29.32707 by 24.7219]

Which formula to use?:
In the case of balloon experiments, we always used the OMM formula.
Indeed, comparative calculations show
- A quasi equivalence of the 2 formula (OMM and Sonntag) for the saturation vapor pressures over ice. Thus there is no incidence, using one or the other formula, on the calculation of the mixing ratio which is the quantity generally used for the studies in stratosphere
- A light variation for the saturation vapor pressure over liquid water, corresponding to a difference of about $\Delta RH = 0.5\%$ on the relative humidity RHw for very humid air at low temperature. The field where the problem of the use of one or the other formula could arise is the cloud microphysics, the threshold for nucleation being highly dependant on the relative humidity. Thus, in the case of the aircraft flights for the study of the cirrus (INCA program), the relative humidity with respect to the liquid phase, RH_W is given, in our data base, from OMM formula and Sonntag one. It is in any case always necessary to specify the formula used (the more so as there are many other formulations)

References

AFNOR : Mesures de l'humidité de l'air: paramètres hygrométriques. Norme NFX 156110, AFNOR 1994

Marti Jacques and Konrad Mausberger, A survey and new measurements of ice vapor pressure at temperatures between 170 and 250K, *Geophys. Res. Lett.*, 20, 5, 363-366, 1993

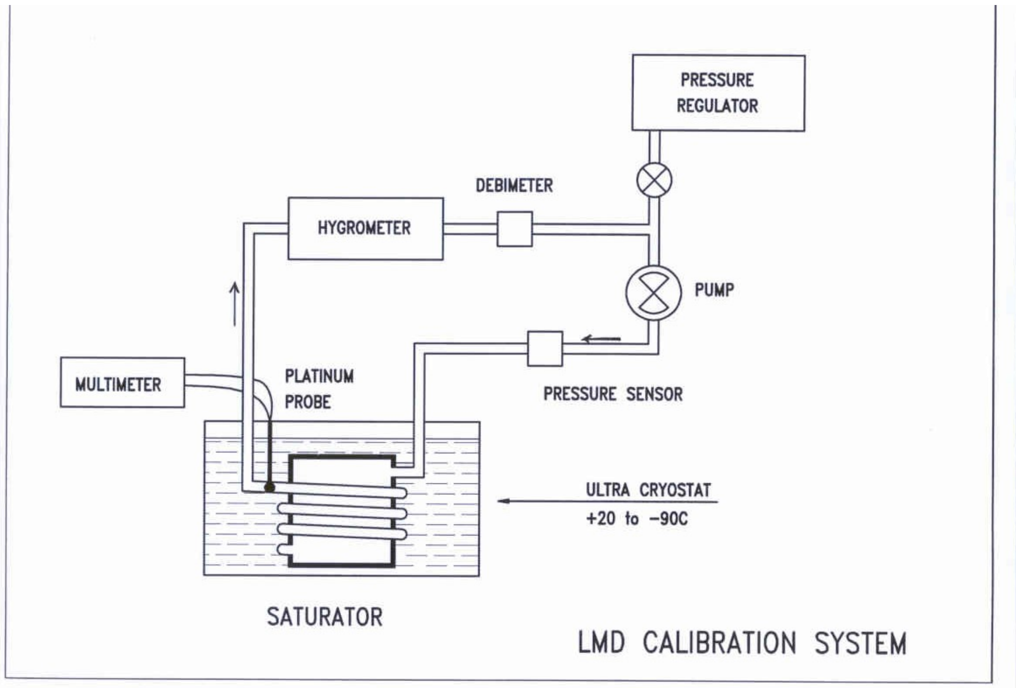
OMM; Réglement technique- Document de base N°2- OMM N°49- Appendices A et B- edition 1984 [The vapor pressure formulation for liquid water given in the 1988 edition has many typographic errors, so that the formula cannot be used! There is in the 2000 edition a "corrigendum to the 1988 edition" and .... it remains an error, hopefully with low consequences on the calculations). However the 1984 edition is correct!]

Sonntag D., Vapor pressure formulations based on the ITS-90 and psychrometric formula – important new values of the physical constants of 1986. Z. Meteorologie 70, 5-340 5-344, 1990

Sonntag D., The history of formulations and measurements of ice vapor pressure, proceedings of the 3d Int. Symposium on Humidity and Moisture, NPL, 93-101, 1998

ANNEX II LMD CALIBRATION SYSTEM FOR LOW HUMIDITY

In that device, as shown on the figure below, the air flows in a closed and tight loop through a saturator which, when the equilibrium is reached, fixes the dew point or frost point temperature of the air which penetrates into the hygrometer. The pressure of the "wet" air is fixed by a pressure regulator, and once the pressure is around the fixed value, the regulator is isolated and the pressure is controlled permanently through the pressure sensor. The saturator contains a small quantity of distilled water to allow the saturation of the air, and plunges in the methanol bath of an ultra-cryostat LAUDA which provides a very fine regulation of its temperature. Thus the temperature of the dewpoint or frost point of the humid air can be fixed between +10 and -90C in a pressure range between 20 and 1000 hPa. The temperature of the saturator is measured by a platinum sensor associated to a multimeter, both connected to the National References with the best levels of uncertainty.



The saturator and the connecting tubes in contact with the "wet air" are in polished stainless steel to reduce outgasing. ,

This unit is a simplified version of the system called "Two Temperatures System" initially built at LMD for the calibration of the sensors with respect to relative humidity, in a wide range of pressure and temperature.

Références

Ovarlez Joëlle, Etalonnage et essais de capteurs d'humidité de l'air, *Mesures,* 36, 12, 82-89, 1971

Ovarlez Joëlle, Calibration techniques and testing hygrometers for horizontal soundings of the troposphere and lower stratosphere, *J. Appl. Meteor*., 11, 3 , 534-540, 1972.

Ovarlez Joëlle, Un système pour l'étalonnage et étude d'hygromètres bas points de rosée, *Bulletin du BNM,* 58, 51-55, 1984

Ovarlez Joëlle, a two temperature calibration system, *proceedings of the 1985 Int. Symposium on Moisture and Humidity*, Washington, Instrument Society of America, ISA – ISBN 0-87664-865-0, , 235-241, 1985.

Ovarlez J., B. Brioit. J. Capus and H. Ovarlez, développement et essais en vols ballon d'un hygromètre à point de rosée pour sondage de l'atmosphère, *Bulletin du BNM*, 69, 9-14, 1987

Wiederhold Pieter R., Ecole Polytechnique Two Temperature Calibration System, France, *Water vapor measurements and instrumentation*, Marcel Decker editor, NY, 174-177, 1997

ANNEX III: PUBLICATIONS

BSO- MIR

Ovarlez J., B. Brioit, J. Capus and H. Ovarlez, Développement et essais en vol ballon d'un hygromètre à point de rosée pour sondage de l'atmosphère, *Bulletin du BNM*, 69, 9-14, 1987

Ovarlez J.. J. Capus, M. Forichon and H. Ovarlez, Mesures in situ d'humidité dans l'atmosphère moyenne, Prosceedings ninth ESA/PAC Symposium on Eropean Rocket and balloon programmes and related research. ESA SP-291, 43-47, 1989

Ovarlez Joëlle, Stratospheric Water Vapor Measurement in the tropical Zone by means of a Frost-point Hygrometer on Board Long-Duration Balloons, *J. Geophys. Res., D8, 15,541-15,545*, 1991.

Ovarlez Joelle, Stratospheric water vapor measurements during CHEOPS-3, *Geophys. Res.Lett.* 18, 4, 771-774, 1991.

Pruvost P., J. Ovarlez, J. Lenoble and W.P. Chu, Comparison of Stratospheric Aerosol and Gas Experiment and Balloon-Borne Stratospheric Water Vapor Measurement, *J. Geophys. Res.*, 98, D3, 4889-4896, 1993.

Ovarlez Joëlle, Stratospheric water vapor measurement in the tropical zone by means of a frost point hygrometer on board long-duration balloons, J. Geophys. Res., 96, 8, 15541-15545, 1991.

Ovarlez J., R. Sadourny and H. Ovarlez, The Amethyste Experiment, Proc. 11th ESA Symp. Eur. Rocket and Balloon Programmes and Related Research, Montreux, Suisse, ESA SP-355, 1994.

Ovarlez Joelle and Henri Ovarlez, Stratospheric water vapor content evolution during EASOE, *Geophys. Res. Lett.*, 21, 13, 1235-1238, 1994.

Teitelbaum H., J. Ovarlez, H. Kelder and F. Lott, Some observations of gravity-wave-induced structure in ozone and water vapour during EASOE, *Geophys. Res. Lett.,* 21, 13, 1483-1486, 1994.

Ovarlez Joëlle, Les mesures in-situ de vapeur d'eau stratosphérique et les programmes de recherche liés aux problèmes d'environnement, Bulletin du BNM. 98, 51-56, 1994

Ovarlez J., H. Ovarlez and H. Teitelbaum, In situ water vapour measurement, a case study of the drying mechanism of the tropical stratosphere, *Quart. J. Roy. Meteorol. Soc*., 122, 1447-1458, 1996.

Schiller C., A. Engel, U Schmidt, R. Borchers and J. Ovarlez, The partitioning of hydrogen species in the Arctic winter stratosphere : Implications for microphysical parameters, J. *Geophys. Res*., 101, D9, 14,489-14,493, 1996 .

Engel A., C. Schiller, U. Schmidt, R. Borchers, H. Ovarlez and J. Ovarlez, The total hydrogen budget in the Arctic winter stratosphere during the European Arctic Stratospheric Ozone Experiment, *J. Geophys. Res*., 101, D9, 14,495-14,503, 1996.

Ovarlez Joelle and Henri Ovarlez, Water vapour and aerosols measurements during SESAME, and the observation of low water vapour content layers, *Air Pollution report 56* on Polar stratospheric ozone, European Commission Bruxelles, 205-208, 1996.

Orsolini Y.J., G.L. Manney, A. Engels, J. Ovarlez, C. Claud and L. Coy, Layering in stratospheric profiles of long lived trace species : Balloon-borne observations and modelling, *J. Geophys. Res*., 103, D5, 5815-5825, 1998.

Claud Chantal, Joëlle Ovarlez and Noëlle A. Scott, Evaluation of TOVS-derived stratospheric temperature up to 10 hPa for a case of vortex displacement over western Europe, *J. Geophys. Res*., 103, D12, 13,743-13,761, 1998.

de La Noë J., J. Ovarlez, H. Ovarlez, C. Schiller, N. Lautié, P. Ricaud, J. Urban, D. G. Feist, L. Zalesak, N. Kämpfer, M. Ridal, D. Murtagh, K. Lindner, U. Klein, K. Künzi, P. Forkman, A. Winnberg, P. Hartogh and A. Engel, Water vapor distribution inside and outside the polar vortex during THESEO, Stratospheric Ozone 1999, *Air Pollution Report 73*, C E C report, 2000.

Haris N.R., J.A. Pyle, J. Ovarlez, H. Ovarlez, P.G. Simmonds, A.D. Robinson, J.C. McIntyre and F. Danis, In situ measurements of CFC11 by DIRAC during THESEO 1999 Campaign, Stratospheric Ozone 1999, *Air Pollution Report 73*, C E C report, 2000.

Voigt C., J. Schreiner, K. Mausberger, J. Ovarlez, H. Ovarlez, C. David, A. Dornbrack, nitric Acid Trihydrate in Polar Stratospheric Cloud Particles, *Science*, 290, 1756-1758, December 2000.

SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapor, WCRP-113, WMO/TD N° 1043, SPARC Report N°2, 312 pages, December 2000

Durry G., A. Hauchecorne, J. Ovarlez , H. Ovarlez, I. Pouchet, V. Zeninari and B. Parvitte , In situ measurement of H2O and CH4 with telecommunication laser diodes in the lower stratosphere: dehydration and indication of a tropical air intrusion at mid-latitudes, *Journal of Atmospheric Chemistry*, 43, 175-194, 2002

Kanzawa H., C. Schiller, J. Ovarlez, et al, Validation and data characteristics of water vapor profiles observed by the Improved Limb Atmospheric Spectrometer (ILAS) and processed with Version 5.20 algorithm, *J. Geophys. Res*., 107, D24, 8217, doi:10.1029/2001JD000881, 2002.

Schiller C, Bauer R, Dörnback A, T. Deshler, H. Ovarlez, J. Ovarlez, F. Stroh, H. Vomel, Dehydration in the Arctic during SOLVE/THESEO 2000 campaigns, *J. Geophys. Res*, 107, D20, doi10.1029/2001JD000463, 2002

Larsen, N., S. Hoyer Svenden, J. Ovarlez et al, Microphysical mesoscale simulations of polar stratospheric cloud formation constrained by in-situ measurements of chemical and optical cloud properties, *J. Geophys. Res.,* 107, 10.1029/2001JD000999, 2002

Durry G., J. Ovarlez and I. Pouchet, Validation of Gomos H_2O data product with balloon-borne laser and frost-point hygrometers, *proceedings of the ENVISAT Validation Workshop*, ESRIN Frascati, 9- 13 December, ESA SP-531, 2002

Voigt, Christiane; Larsen, Niels; Deshler, Terry; Kröger, Chris; Schreiner, Jochen; Mauersberger, Konrad; Luo, Beiping; Adriani, Alberto; Cairo, Francesco; Di Donfrancesco, Guido; Ovarlez, Joelle; Ovarlez, Henri; Dörnbrack, Andreas; Knudsen, Bjørn; Rosen, Jim In situ mountain-wave polar stratospheric cloud measurements: Implications for nitric acid trihydrate formation J. Geophys. Res. Vol. 108 No. D5 10.1029/2001JD001185, 2003

Schreiner J., C. Voigt, K. Mausberger, J. Ovarlez et al, Chemical microphysical, and optical properties of polar stratospheric clouds, *J. Geophys. Res.,* 108, D5, 8313, doi:10.1029/2001JD000825, 2003

Deshler Terry, N. Larsen, Christoph Weisser, Jochen Schreiner, Konrad Mauersberger, Francesco Cairo, Alberto Adriani, Guido Di Donfrancesco, Joelle Ovarlez. Henri Ovarlez, Ulrich Blum, K. Fricke, Andreas Dörnbrack, Large nitric acid particles at the top of an Arctic stratospheric cloud, *J. Geophys. Res.,*108. D16. 4517, DOI:10.1029/2003JD00347, 2003

Ovarlez J. et al, Water vapour measurements in ice clouds in the upper troposphere and in the middle stratosphere, *Proceedings of the Sixth European Symposium on Ozone*, Göteborg, Sweden, Air Pollution, Report EUR 20650, 349-352, 2003

Bureau Jérôme, Joëlle Ovarlez, Jean Baptiste Renard, Georges Dury and Patrick Wursteisen, Validation of GOMOS water vapour, temperature and ozone products with balloon borne instruments during the Kiruna winter campaign 2002-2003. *Proceedings of the 16th ESA symposium on European rockets and balloon programmes and related research* ST Gallen, Switzerland, ESA SP-530, 457-461, 2003

Spichtinger P., K. Gierens, H. Smit, J. Ovarlez , and J.F. Gayet , On the distribution of relative humidity in cirrus clouds, *Atmospheric Chemistry and Physics Discussions*, 4, 365-397, 2004

Weisser C., K. Mausberger, J. Schreiner, N. Larsen, F. Cairo, A. Adriani, J. Ovarlez and T. Deshler, Composition analysis of liquid particles in the Arctic stratosphere, *Atmospheric Chemistry and Physics Discussions*, 4, 2513-2531, 2004

Larsen N., B. M. Knudsen, S. H. Svendsen, T. Deshler, J. M. Rosen, R. Kivi, C. Weisser, J. Schreiner, K. Mauerberger, F. Cairo, J. Ovarlez, H. Oelhaf, R. Spang Formation of solid particles in synoptic-scale Arctic PSCs in early winter 2002/2003, *Atmospheric Chemistry and Physics Discussions*, 4, 2485-2512, 2004

Oelhaf H., A. Fix, C. Schiller, K. Chance, W. Gurlit, J. Ovarlez, J. B. Renard, S. Rohs, G. Wetzel, T.M. von Clarman, M. Milz, D.Y. Wang, J. Remedios and A.M. Waterfall, Validation of MIPAS-ENVISAT version 4.61 Operational data: H2O, *Proceedings of the ENVISAT ACVE2 Validation workshop*, 3-7 May 2004, Frascati, ESA SP-562, 2004.

Blom C. E., C. Camy-Peyret, V. Catoire, K. Chance, H. Oelhaf and J. Ovarlez, Validation of MIPAS Temperature Profiles by Stratospheric Balloon and Aircraft Measurements, *Proceedings of the ENVISAT ACVE2 Validation workshop*, 3-7 May 2004, Frascati, ESA SP-562, 2004.

Renard J.B., G. Berthet, A. Bracher, V. Catoire, M. Chartier, B. Gaubicher, F. Goutail, N. Huret-Brun, H. Oelhaf, J. Ovarlez, J. P. Pommereau, C. Robert and G. Wetzel, Validation of GOMOS vertical profiles using balloon-borne instruments and satellite data, *Proceedings of the ENVISAT ACVE2 Validation workshop*, 3-7 May 2004, Frascati, ESA SP-562, 2004.

Durry G., N. Amarouche, V. Zéninari, B. Parvitte, T. Lebarbu, and J. Ovarlez, In situ sensing of the middle atmosphere with balloonborne near-infrared laser diodes, Spectrochimica Acta Part A 60, 3371-3379, 2004

Ovarlez Joëlle, Evolution de la quantité de vapeur d'eau stratosphérique, Lettre Pigb-Pmrc France – Changement global, N° 17, 2-7, 2005

Durry G., Zeninari V., Parvitte B., Le Barbu T., Lefevre F., Ovarlez J. and Gamache R.R., Pressure-broadening coefficients and line strengths of H2O near 1.39 µm: application to the in situ sensing of the middle atmosphere with balloon-borne diode lasers, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 94, 3-4, 387-403, 2005.

AIRCRAFT

Ovarlez Joelle, Henri Ovarlez Rose-Marie Philippe and Eric Landais, Water vapour measurements during the POLINAT campaign, *Air Pollution Report N°58*, Office of Publication of CEC, Bruxelles, 1996.

Ovarlez Joëlle and Peter van Velthoven, Comparison of water vapor mesaurements with data retrieved from ECMWF analyses during POLINAT experiment, *J. of Appl. Meteorol.*, 1329-1335, 1997.

Schlager H., P. Konopka, P. Schulte, U. Schumann, H. Zeiries, F. Arnold, M. Klemm, D. Hagen, P.D. Whitefield and J. Ovarlez, In situ observations of air trafic emission signatures in the North Atlantic flight corridor, *J. Geophys. Res*., 102, D9, 10, 750-10,739, 1997.

Ovarlez Joelle, Henri Ovarlez, Rose Marie Philippe and Jacques Capus, Water Vapor measurements during POLINAT2 experiment, *Air Pollution Research Report N° 68*, Report, Office of Publication of CEC, Bruxelles, 1998.

Ovarlez Joëlle, Henri Ovarlez and Jacques Capus, Atmospheric water vapour measurements with an aircraft-borne cryogenic frost-point hygrometer, *proceedings from* 3d *International symposium on humidity and moisture*, published by National Physical Laboratory, London, 1998

Ovarlez Joëlle, Peter van Velthoven and Hans Schlager, Water vapor measurements from the troposphere to the lowermost stratosphere : Some signature of troposphere to stratosphere exchanges, *J. Geophys. Res*., 104, 16,973-16,978, 1999

Helten M., H.G. Smit, D. Kley, J. Ovarlez, H. Schlager, R. Baumann, U. Schumann, P. Nedelec and A. Marenco, In-Flight comparison of MOZAIC and POLINAT Water Vapor Measurements, *J. Geophys. Res.* Vol. 104, D21, 26087-26096., 1999.

Vay S. A., G. W. Sachse, J. Ovarlez, J. Podolske, B. E. Anderson, Nolf, T. Slade, P. Bui, Tropospheric water vapor measurements over the North Atlantic during SONEX, *J. Geophys. Res*., 105, D3, 3745-3755, 2000

Ovarlez, J., P. van Velthoven, G. Sachse, S. Vay, H. Schlager, H. Ovarlez, Comparison of water vapor measurements from POLINAT 2 with ECMWF analyses in high humidity conditions, *J. Geophys. Res*., 105, D3, 3737-3744, 2000.

Schumann U., H. Schlager, F. Arnold, J. Ovarlez, H. Kelder, O. Hov, G. Haymann, I.S.A. Isaksen, J. Stahelin, and P. Whitefield, Pollution from aircraft in the North Atlantic flight corridor : Overview on the Polinat Projects, *J. Geophys Res*., 105, D3, 3737-3744, 2000.

J. Ström, U. Schumann, J.F. Gayet, J. Ovarlez, F. Flatoy, M. Kumala, O. Schrems, P. Minnis, S.B. Diaz, B. Milicic, V. Valderama, E. Amthauer, J. Petterson, and F. Arnold, Aerosol and Cirrus Measurements at Mid Latitudes on the Southern Hemisphere, -An Overview based on the first INCA Experiment, Proceedings of the A2C3 (Aviation, Aerosols, Contrails and Cirrus Clouds) workshop, Seeheim Germany, July 10-12 2000, Schumann U. and G. T. Amanatidis Editors, *Air Pollution Report 74*, *EUR 19428*, European Commission Brussels, pp 211- 214, 2000 .

Ovarlez Joëlle, Hans Schlager, Peter van Velthoven, Eric Jensen, Ulrich Schumann, Henri Ovarlez, and Johan Ström, Water Vapour in the upper troposphere from POLINAT and other campaigns, Proceedings of the A2C3 (Aviation, Aerosols, Contrails and Cirrus Clouds) workshop, Seeheim Germany, July 10-12 2000, Schumann U. and G. T. Amanatidis Editors, *Air Pollution Report 74*, EUR 19428, European Commission Brussels, pp 177-180, 2000.

SPARC Assessment of Upper Tropospheric and Stratospheric Water Vapor, WCRP-113, WMO/TD N° 1043, SPARC Report N°2, 312 pages, December 2000

Jensen Eric, Owen Toon, Stéphanie Vay, Joëlle Ovarlez, Randy May, Paul Bui, C.H. Twohy, B. Grandud, R. Pueschel and U. Schumann, Prevalence of ice supersaturated regions in the upper troposphere : implication for Optically thin ice cloud formation, *J. Geophys. Res,* 106, D3, 17,253-17,266, 2001.

Ovarlez Joëlle, Eric Jensen, Henri Ovarlez, Hans Schlager, Ulrich Schumann, Stéphanie Vay and Peter van Velthoven, Water Vapour in the upper troposphere and lowermost stratosphere from POLINAT campaigns measurements, Proceedings of the A2C3 (Aviation, Aerosols, Contrails and Cirrus Clouds) workshop, Frankfort, July 2000, CEC *Air Pollution Report N° 74*, 2001.

Ovarlez Joëlle, Jean- François Gayet, Klaus Gierens, Johan Ström, Henri Ovarlez., Frédérique Auriol, Reinhold Busen and Ulrich Schumann., Water vapour measurements inside cirrus clouds in Northern and Southern hemispheres during INCA, *Geophys Res. Lett,* 29, 16, 10.1029/2001GL014440, 31 August 2002

Gayet J.F., F. Immler, F Auriol, A. Minikin. A. Petzoldt, J. Ovarlez and J. Ström, Microphysical and optical properties of a wave-cirrus sampled during INCA experiment, Paper presentation at 11th Conference on cloud physics, American meteorological society, 3-7 June 2002, Ogden, Utah

Ström, J., M. Seifert, B. Kärcher, J. Ovarlez, A. Minikin, J. F. Gayet, R. Krejci, A. Petzold, F. Auriol, R. Busen, U. Schumann, W. Haag, and H. C. Hansson, Cirrus cloud occurrence as function of ambient relative humidity: A comparison of observations from the Southern and Northern Hemisphere midlatitudes obtained during the INCA experiment, *Atmos. Chem. Phys. Discuss.*, 3, 3301-3333, 2003

Haag, W., B. Kärcher, J. Ström, A. Minikin, U. Lohmann, J. Ovarlez, and A. Stohl, Freezing thresholds and cirrus cloud formation mechanisms inferred from in situ measurements of relative humidity, *Atmos. Chem. Phys.*, 3, 1791-1806, 2003

Seifert, M., J. Ström, R. Krejci, A. Minikin, A. Petzold, J.-F. Gayet, U. Schumann, and J. Ovarlez, In situ observations of aerosol particles remaining from evaporated cirrus crystals: Comparing clean and polluted air masses, *Atmos. Chem. Phys.*, 3, 1037-1049, 2003.

Seifert, M., J. Ström, R. Krejci, A. Minikin, A. Petzold, J.-F. Gayet, H. Schlager, H. Ziereis, U. Schumann and J. Ovarlez, Thermal stability analysis of particles incorporated in cirrus crystals and of non-activated particles in between the cirrus crystals: Comparing clean and polluted air masses, *Atmos. Chem. Phys. Discuss.*, 3, 3659–3679, 2003.

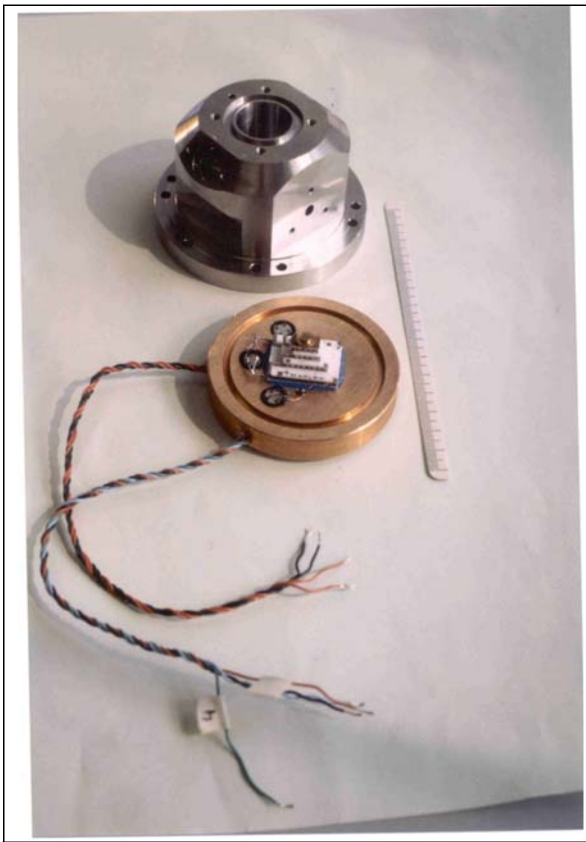
Seifert, M., J. Ström, R. Krejci, A. Minikin, A. Petzold, J.-F. Gayet, H. Schlager, H. Ziereis, U. Schumann and J. Ovarlez Aerosol-cirrus interactions: A number based phenomenon at all?, *Atmos. Chem. Phys.*., 4, 293-305, 2004.

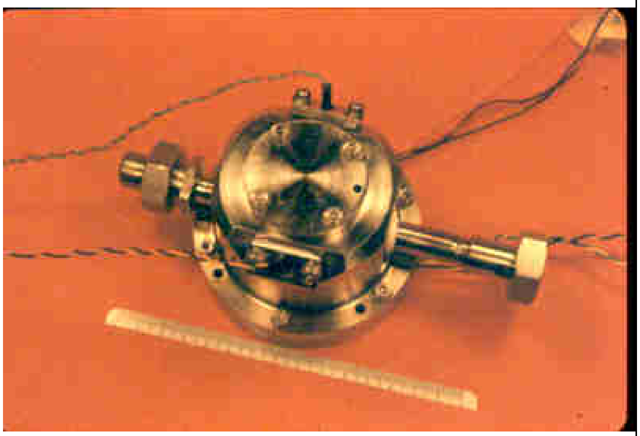
Gayet, J.-F., J. Ovarlez, V. Shcherbakov, J. Ström, U. Schumann, A. Minikin, F. Auriol, A. Petzold, and M. Monier, Cirrus cloud microphysical and optical properties at southern and northern midlatitudes during the INCA experiment, *J. Geophys. Res,*109, D20206, doi:10.1029/2004JD004803, 2004.

Krämer M, C. Schiller, H. Ziereis, J. Ovarlez and H. Bunz, Nitric acid partitioning in cirrus clouds: the role of aerosol particles and relative humidity, submitted to *Tellus*, 2005

Gayet, J.F., . Shcherbakov, H. Mannstein, A. Minikin, U. Schumann, J. Ström, A. Petzold, J. Ovarlez and F. Immler, Microphysical and optical properties of high altitude clouds observed in mid-latitudes southern hemisphere during INCA, submitted *J. of Atmos. Sci.*, 2006.

ANNEX IV ILLUSTRATIONS



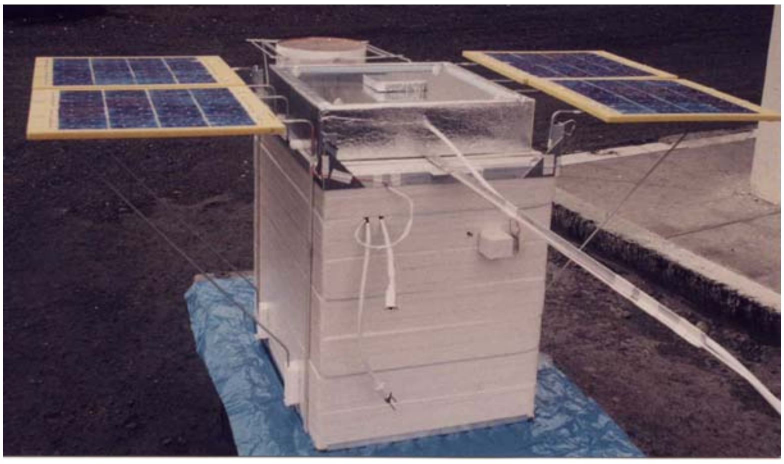


Hygrometer with Peltier :

The mirror is stuck on a 4 stages Peltier module which is stuck on a copper heat sink. On the right, the picture shows the sensor head which is closed and tight. The holders of the optical transmitter and receiver are seen (cf figure 1).

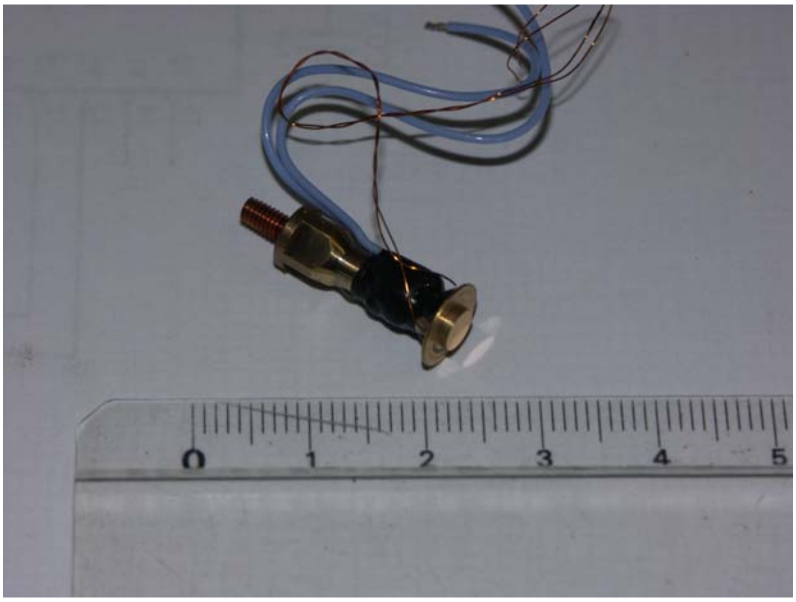
The hygrometer payload for MIR flights

On the left side the holder for the air temperature sensor and for the air inlet tube
On the right side, the ARGOS antenna.

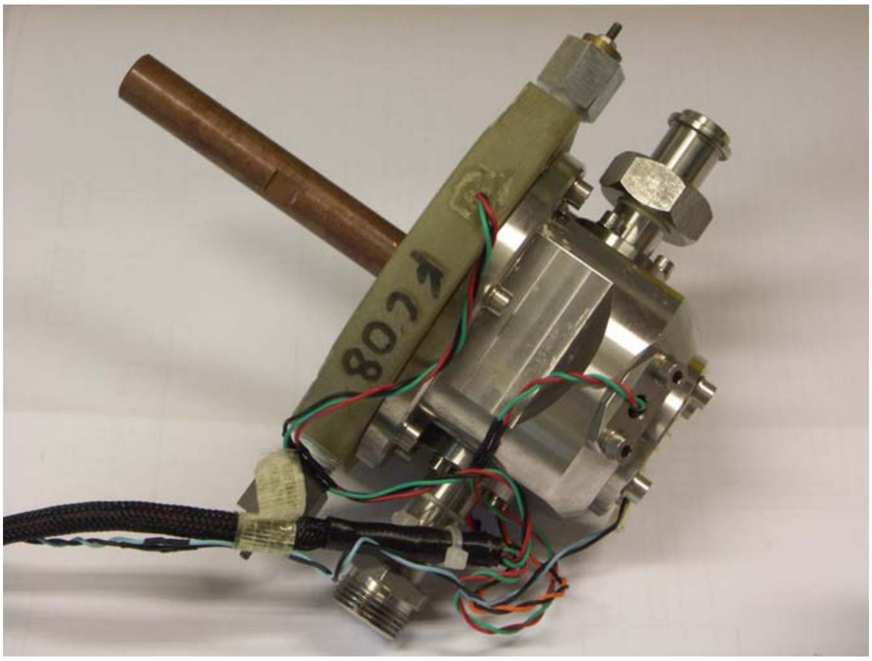


The hygromter payload for MIR flights.
The solar cells panels are seen.
The heat sink is above: it is an aluminium plate with an aluminised polystyrene support

The MIR ready to be launched (Pretoria, South Africa)



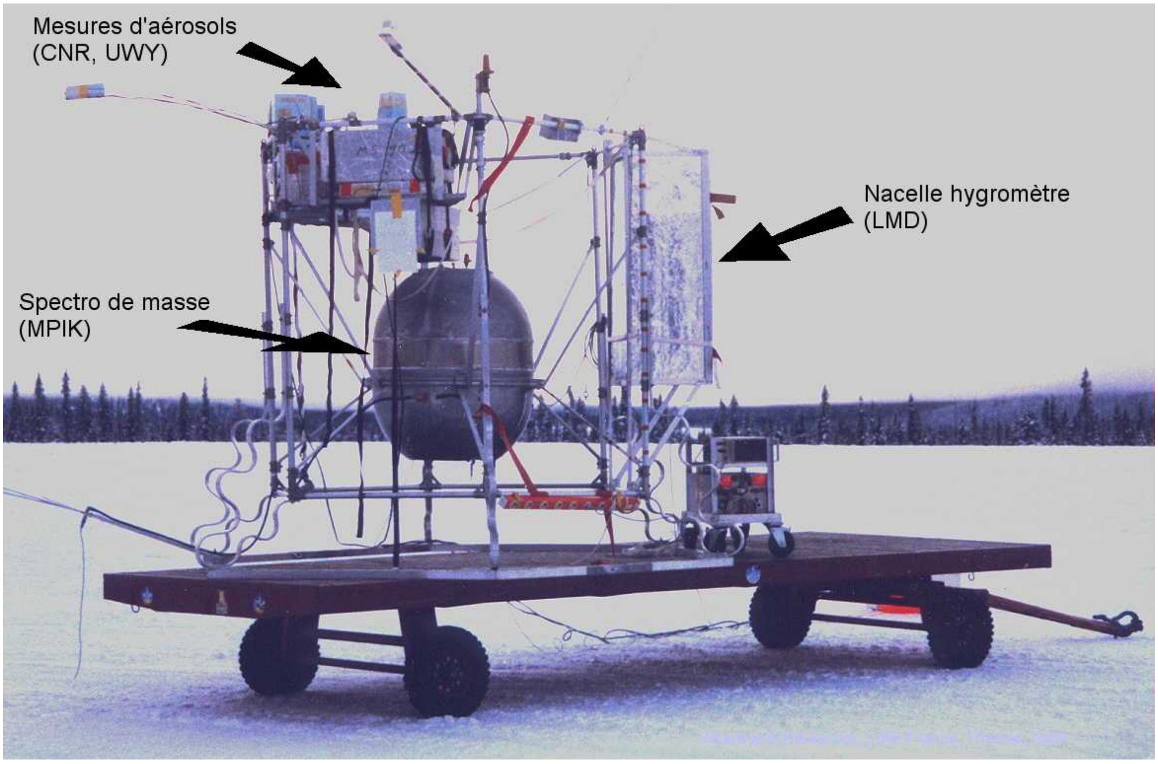
<u>The cryogenic hygrometer</u> :
The mirror is on a thin rode. A resistance wire is wrapped around the rode



<u>The hygrometer head</u>

The tube to be plunged in liquid nitrogen is seen.
Except the tube, the hygrometer head is the same as the one of the Peltier hygrometer.
The mechanical connections seen are to link the hygrometer head to the calibration system with tight connections.

The hygrometer payload for BSO, ELHYSA, here with Bertrand Gaubicher



The LMD hygrometer onboard the payload of Max Plank Institute, Heidelberg.
(PSC Analysis and CIPA european programs during THESEO)

The hygrometer for aircraft

The cryogenic hygromter inside the aircraft with Jacques Capus
(here the Falcon, research aircraft from DLR –Deutsches Zentrum fûr Luft und Raumfart)