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1 Executive Summary

Introduction

The effects of climate change are expected to be widespread and substantial, and robust climate data and models are needed to predict and mitigate their social and economic impacts. This project reduced the measurement uncertainties of essential climate variables by developing methods to trace and calibrate measurements to their underlying SI unit definitions. These techniques will be used to increase the accuracy of climate measurements, supporting the development of improved climate models.

The Problem

Climate change threatens ecosystems, economies, and the quality of life in Europe and the rest of the world*. Its effects are likely to be as complex as they are damaging – accurate and reliable climate modelling is needed to understand and mitigate the effects of climate change.

The effectiveness of climate modelling depends upon the quality of the data upon which the models are founded. To ensure climate data continues to be consistent and of high-quality, standard global protocols are needed for improved temperature, humidity, pressure and airspeed measurements, traceable to measurement standards.

Specifically, before this project: improved calibration methods were needed to reduce the uncertainties of air temperature and airspeed measurements. Measuring humidity is important but challenging, due partly to the wide disparity in atmosphere water content in different locations, and improved primary techniques were needed for more accurate humidity measurement. Once established, calibration methods were then needed to validate field measurements against the improved primary standards. Weather stations distributed throughout the world operate in a wide range of environmental conditions, which effect their measurements in different ways. In-situ calibration methods were needed for weather stations to correct for interference from environmental conditions. Sources of measurement uncertainty in historical temperature data also needed to be identified, to assess their accuracy and to allow for consistent comparisons across datasets.

* *IPCC Climate Change 2014 Synthesis Report Summary for Policymakers.*

The Solution

The overall goal of this project was to reduce measurement uncertainties of both historic and future climate measurements. To achieve this, objectives 1 to 6 focussed on developing methods to calibrate temperature, airspeed and humidity measurement instruments. Objectives 7 to 10 developed calibration methods for automatic weather stations. Objective 11 focussed on understanding and minimising the sources of measurement uncertainty in historic temperature datasets.

Impact

This project has spearheaded an increasing focus on the measurement of climate variables in the metrological community. Technical groups have been established in key metrology institutions, such as the CIPM Consultative Committee for Thermometry, and the EURAMET Technical Committee for Thermometry, putting climate and weather firmly on the agenda. In addition, nominees from the metrology community have been appointed by invitation to World Meteorological Organisation (WMO) Expert teams. This provides a framework for long-term collaboration, and ensures metrology expertise is available to WMO decision-making groups, supporting the development of best practice meteorology and climate science. The achievements of MeteoMet will also be further developed in the follow-on MeteoMet2 project, where improved measurement techniques will be developed for a wider set of climate variables under a broader range of conditions.

The calibration service and the new traceable measurement procedures developed in the project are already being used by meteorological and climate organisations, such as SMI, Observatory of Ebro and Climate Consulting, to improve the accuracy of their observations, and their climate models and analysis.

The new instruments developed, and the comparison exercises involved in the project, were carried out in collaboration with a range of manufacturers, including Vaisala, CAE, MODEM, Luft, Rotronic, Thies, Setra, Seac, E+E. The results of this project are being used by these companies to develop the next generation of weather and climate measurement instruments.

Ultimately, by ensuring that climate measurements are traceable to their underlying SI unit definitions, measurement uncertainties in climate data will be reduced, and the accuracy of climate models can be improved. In the short-term, weather forecasts and weather warning systems can be made more exact, supporting a range of economic sectors including energy, transport, and agriculture. Over the longer-term, more accurate climate models are crucial to monitor and predicts the progress of climate change, and will help in the mitigation of its potentially severe social and economic effects.

2 Project context, rationale and objectives

Recent decades have seen notable changes in the global and European climate, together with an increased desire to both monitor climate change and reduce the impact of human activity on the climate. The need to improve data has been expressed by different climate data users such as climatologists, economists and politicians.

To address data gaps and enable the development of a sustained integrated monitoring and observation system for Europe this project responded to some principal needs:

Traceability for air temperature and wind speed measurements

Although standard operating procedures and data quality objectives are in place for some measurements, extensions to a wider range of applications and parameters (temperature, pressure, humidity, wind speed, solar radiance) and improvements in existing procedures are necessary. Routine calibration procedures are generally not adopted for most of the measurements but are necessary to maintain a high level of confidence in the quality of the data.
Moreover, the communication between NMIs and national institutes or local agencies interested in climate observations has to be enforced in order to overcome the current fragmentation of information and approaches and to improve measurement capability to meet the needs of stakeholders.

Uncertainties in thermometer calibration are a critical parameter in estimating an uncertainty budget for temperature measurements. Some NMIs in Europe can calibrate air temperature sensors in air with an expanded uncertainty of around 0.08 °C, but meteorologists and other users need both smaller calibration uncertainties and better understanding of the calibration uncertainties.

Improving humidity sensors and calibration methods

The humidity of air in terms of the volume concentration of water is a key parameter to be measured for understanding climate processes all over the world. A big challenge for humidity sensors of every type is the wide dynamic range of more than a factor of 10000 of water content in the atmosphere.

Errors in upper-air observations due to the effect of solar radiation on temperature measurements and the uncertainty of saturation water vapour data are issues that require detailed study. Better instruments with smaller calibration uncertainties are required by the meteorological community.

Field calibration of hygrometers is an important factor to ensure the achievement of reliable and comparable atmospheric humidity data, especially when long-term measurements are being be evaluated. National primary humidity standards provide highest quality gas mixtures with low measurement uncertainties, but cannot be brought to the field for on-site calibration, so that the field hygrometers have to be removed from the initial measurement location and shipped to the primary humidity standard. This severely limits the calibration frequency, creates questions on the validity and transferability of the lab-based primary calibration for field measurements and consequently asks for field compatible transfer standards which allow checking the instrument response on-site, at close to field conditions.

Numerous humidity sensors have been developed for atmospheric measurements on platforms, from ground based to airborne such as planes or balloons, together with basic protocols for their calibration. The very few intercomparisons undertaken to validate the performance of field instruments have however revealed significant discrepancies (10% or more) even for the best and well established instruments. Comparing the results and methods shows also a severe lack of consistent calibration protocols and traceability to national humidity standards. In order to provide reliable atmospheric humidity data especially in field conditions, improved calibration instruments and protocols need to be developed and established to assure traceability to national standards.

An important influence on the uncertainty of water vapour measurement data comes from the water vapour equation. Improvement in the uncertainty of the water vapour formula in the temperature range between -80 C and +100 °C is needed for the improvement of primary standards in the field of hygrometry. Target relative uncertainties vary between 0.85% and 0.04%, according to the temperature range. Better uncertainties of primary standards will enable improvements in the calibration of instruments used for water vapour fraction measurements in the atmosphere, especially where the water vapour fraction is at the level of some parts per million (ppm).

Calibration of reference radiosondes

In 2007, the Global Climate Observing System (GCOS) of the WMO laid out the need for a GCOS Global Reference Upper-Air Network, or GRUAN. Current upper air measurement networks do not meet the accuracy and detail of observations needed to specify climate variability and changes above the Earth's surface (WMO, 2007). To meet GRUAN's requirements for the reliability of humidity measurements, improved traceable calibration methods are needed. GRUAN specifies the target relative accuracy and precision in the stratosphere of 2 % and 5 % respectively in terms of the mixing ratio. A key factor in achieving the required reliability of data is the traceability of radiosonde sensor measurements through appropriate calibration. However, humidity calibrations in conditions equivalent to Upper Troposphere and Lower Stratosphere with conventional systems are very time consuming and not suitable in this context.

Calibration of automatic weather stations

Weather stations need to be equipped with calibrated sensors in order to improve the reliability of measurements. Accurate methods for in-situ calibrations of weather stations, including those operating in extreme weather conditions, are required. Input from NMIs in defining procedures, developing capabilities, calibration standards and traceability chains is necessary.

Robustness of the historical temperature measurement data

Historical data series often lack clear statements on the measurement techniques, sensors, calibration uncertainty, and traceability to standards and temperature scales, making it difficult to assess the reliability of the data and to compare the data of the different periods.

The project therefore focused on the following main objectives:

Traceability for air temperature and wind speed measurements

1. Development of accurate laboratory calibration facilities and procedures for air temperature sensors (target calibration uncertainty of air temperature sensors of below 0.05 °C, over a temperature range between -20 °C to +50 °C)
2. Development of a method for establishing traceability for wind speed measurements

Improving humidity sensors and calibration methods

3. Realisation of traceable, self-calibrating tunable diode laser (TDLAS) hygrometers and the study of absorption lines of water molecule
4. Intercomparison of airborne field humidity sensors of different types (Aquavit 2 campaign)
5. Generation of new data to improve the water vapour formulae and proposition of a new equation for the water vapour pressure curve
6. Novel methods and instruments for the measurement of temperature, humidity, and pressure in the lower and upper atmosphere. Implementation of new hygrometers based on microwave resonances in quasi-spherical cavities, innovative multisensors for free-space non-contact atmospheric measurements, novel methods for GPS and Galileo-based measurements.

Calibration of reference radiosondes

7. Development of a novel calibration system comprising a measurement chamber with highly optimised heat and mass transfer characteristics for establishing traceability for radiosonde-based measurements

Calibration of automatic weather stations (AWSs)

8. Proposal for AWS calibration methods and protocols and evaluation of the effect of solar radiance and ageing on weather stations.
9. Development of facilities for laboratory and in situ simultaneous calibration of temperature, humidity and pressure sensors in weather stations, including those operating under extreme environmental conditions.
10. Development of protocols for software validation of automatic weather stations (AWSs).

Robustness of the historical temperature measurement data

11. Investigation of uncertainties sources in historical temperature data.

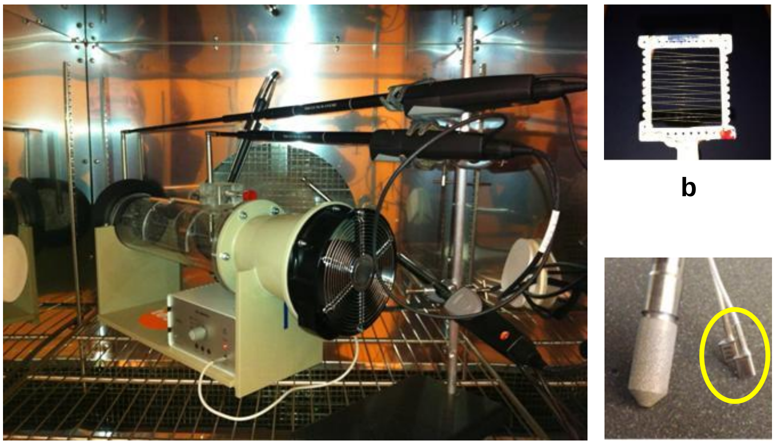
3 Research results

3.1 Traceability for air temperature and wind speed measurements

Objective 1: Development of accurate laboratory calibration facilities and procedures for air temperature sensors

The aim of this objective was to reduce the calibration uncertainty of air temperature sensors from a typical expanded uncertainty of 0.08 °C to a target uncertainty below 0.05 °C, in a temperature range between -20 °C to +50 °C.

NPL developed a facility for improved laboratory calibrations for air temperature sensors (Figure 1). Material detailing recommendations and uncertainty analysis (Figure 2) for accurate calibration and use of air temperature sensors was developed and presented at MMC 2014 International workshop (15-17 September 2014). The content of the presentation was made available for inclusion in the guidance.



a b c

Figure 1: a) calibration facility for air temperature sensors developed at NPL; b) meteorological fine-wire PRT (source: University of Reading); c) quartz crystal resonance thermometer (circled, source: ISSP, Bulgaria) shown alongside a hygrometer probe.

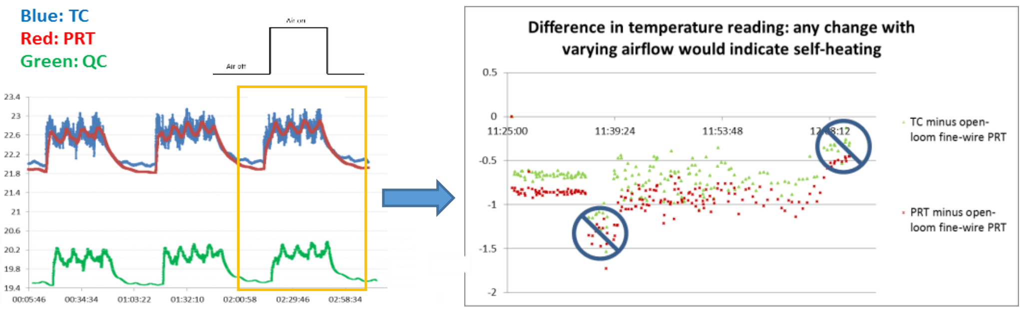


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Figure 2: results of temperature measurements in the NPL facility

Conclusion - Objective achieved: Laboratory calibration facilities and procedures for air temperature sensors were developed, reducing measurement uncertainty from 0.08 °C to the level of less than 0.05 °C (within a temperature range between -20 °C to +50 °C).

Objective 2: Development of a method for establishing traceability for wind speed measurements

With a novel **laser based anemometer** developed at PTB on-site wind speed measurements at measurement heights of 10 m and 50 m were performed in different terrains and related to simultaneously measured data of an ultrasonic anemometer 10 m above ground. In advance TUBITAK calibrated the ultrasonic anemometer according to international standards for the calibration of ultrasonic anemometers in a wind tunnel considering humidity and temperature variances and DTI performed investigations with respect to the influence of several different deposits on an ultrasonic anemometer including different degrees of rain. It has been shown that on-site calibrations of anemometers with a laser based anemometer as a reference standard are promising to ensure traceable wind speed measurements without anemometer replacement provided that the reference measurement position is close to the anemometer to be calibrated so that interactions between the anemometer and the reference standard can be neglected or excluded.

The calibration setup established to investigate **calibration** behavior of **ultrasonic anemometers** for varying temperature and humidity conditions in the laboratory is shown in the Figure 3. The measurements at TUBITAK were limited with the laboratory fixed climate conditions but now it is possible to adjust temperature and humidity in the laboratory to make measurements in the wind tunnel. The calibration procedure obtained from the measurement results with setup was reported. The procedure was used to evaluate the humidity and temperature effects on the sonic anemometers in a defined range of temperature and humidity.

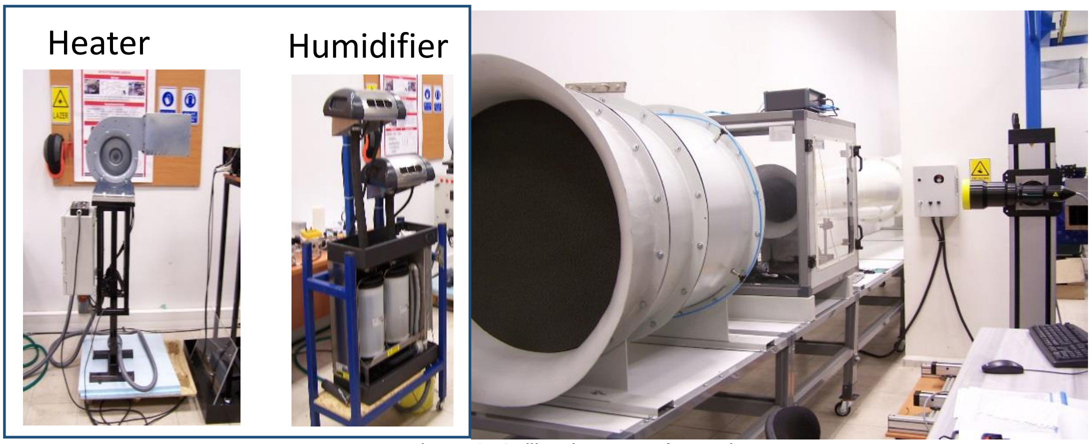


Figure 3. Calibration setup for sonic anemometers

The procedures for **calibration of sonic anemometers** explained in the ISO 16622 and ASTM D 6011-96 are evaluated to be suitable also for measurements implementing the different environmental conditioning in the wind tunnel. There is no need for a new standard to make tests for varying environmental conditions.

LIDAR calibration and laboratory calibration results should be correlated to come up with a final on-site calibration procedure for sonic anemometers. The LIDAR measurements made by PTB and it has been reported that there were still some problems to overcome with LIDAR measurements. So it can be concluded that traceability chain of sonic anemometers will continue to depend only on the laboratory measurements until the laboratory and LIDAR results are managed to be correlated successfully.

The DTI has investigated the **influence of several different deposits on ultrasonic anemometers** manufactured by Vaisala (WMT50 and WMT52). The work was focused on testing the effect of calibration and environment on ultrasonic anemometer measurements. Measurement uncertainty was found to be a complex quantity influenced by among other things the amount of seeding used during the calibration procedure. Heavy seeding levels was found to influence the measurements, however the effect of seeding was difficult to model, and consequently no systematic effects could be established. Additionally, the results showed that ice formation on the ultrasonic transducers might lead to misleading and erroneous anemometer output. Rain was found to cause no significant effect on the anemometer read out. Finally, the anemometer blockage effect was fully characterised, which can be used for preparing wind tunnel calibration procedures.

Figure 4: Vaisala AWS under test

Conclusion - Objective achieved: A novel **laser based anemometer** was developed at PTB for establishing robust traceability and improved spatial and temporal resolution to on-site wind speed measurements. An experimental setup was made to investigate calibration behaviour of ultrasonic anemometers for varying temperature and humidity conditions and a procedure was developed to evaluate the humidity and temperature effects on the sonic anemometers' performance. The influence of deposits on ultrasonic anemometer reading was evaluated and revealed significant contribution for ice and negligible influence for rain. The blockage effect was also fully characterised.

3.2 Improving humidity sensors and calibration methods

Objective 3: Realisation of traceable, self-calibrating tunable diode laser (TDLAS) hygrometers and the study of absorption lines of water molecule

This objective dealt with new optical cells for the Tuneable Diode Laser Absorption Spectrometer (TDLAS) and the exact and traceable measurement of the line parameters for the water absorption line with pressure and temperature dependence.

During this project the **optical cells** to be used in the extractive TDLAS hygrometer have been designed. Two cells have been designed, which enable the measurement of H_2O concentrations in the range of a few ppm up to 50000 ppm. A single-pass cell is used for higher H_2O concentrations (800-50000 ppm), while a multi-pass cell is used for lower H_2O concentrations (1-1000 ppm). Switching between the two cells can be performed by means of a moveable mirror. The cells, together with the laser and the detector, will be placed in a sealed housing purged with dry air or nitrogen to minimise light absorption by water vapour outside the optical cells.

Set-up of the optical cells is depicted in Figure 5:

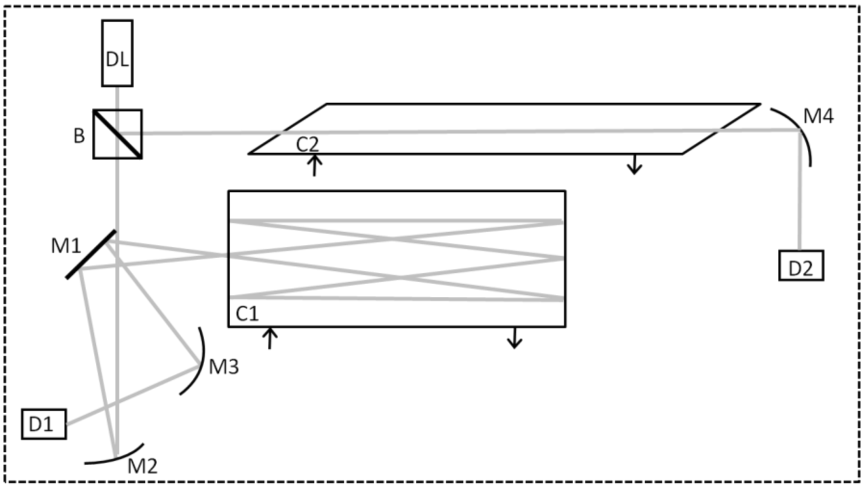


Figure 5: Optical set-up with two cells. L: laser, D1, D2: detectors, C1: single-pass cell used for high H2O concentration measurements, C2: multi-pass cell used for low H2O concentration measurements, M1: plane mirror, M2, M3, M4: parabolic mirror, B: beam splitter, arrows indicate the gas inlet and outlet ports

Single-pass cell

A single pass absorption gas cell made of stainless steel has been constructed. The cell has a nominal length of 77 cm and is suitable for measurements in the pressure range 0-1000 hPa at ambient temperatures. The cell volume is ~100 cm^3. The windows of the cell are made of sapphire and placed at Brewster angle (60.5°) to minimise optical fringes. The achieved fringe level is $5*10^{-4}$.

This fringe level allows measurement of absorbances down to 5•10-2 (which corresponds to a concentration of 800 ppm while probing a chosen H2O transition at 1.37 µm, at ambient conditions) with a signal to noise ratio better than 100. The minimum detectable concentration with this cell is estimated to be around 25 ppm (an absorbance of 1.5•10-3 and a signal to noise ratio of ~3) for a measurement time of 1 second.

For a chosen water transition at 2.7 µm, the absorbance level of 5•10-2 corresponds to a concentration of 85 ppm (with a signal to noise level better than 100) at ambient conditions. The minimum detectable concentration probing the H2O line at 2.7 µm is ~2.5 ppm for a signal to noise level of 3 and a measurement time 1 second.

The highest measureable concentration is limited by the vapour pressure of water at room temperature (~26 mbar, corresponding to a concentration of 26000 ppm at 1000 hPa), and can be further extended to 50000 ppm by slightly heating the cell and the gas handling line.

Path length of the single pass cell has been determined by mechanical measurements, as well as by a spectroscopic method. Results obtained using the two length measurement methods agree within their uncertainties. The length of the cell is 774 mm, with an expanded uncertainty of 2 mm (k = 2).

Multi-pass cell

For measuring lower concentrations, a commercial astigmatic Herriott-type multipass cell with 36 m path length will be used. The cell is made of aluminium and glass. The length of the base path is 20 cm and the cell volume is 300 cm3. The laser light beam is focused into the cell using parabolic mirrors.

Taking into account the fringe level measured in the cell and the line strength of the chosen H2O absorption lines at 1.37 µm, a signal to noise ratio of ~10 is estimated for the measurement of 1 ppm H2O at ambient conditions, while the minimum detectable concentration is estimated to be 0.3 ppm (signal to noise ratio of ~3) for a measurement time of 1 second.

For this 36 m multipass gas cell, utilising the chosen H2O transition at 2.7 µm and ambient temperature and pressure, a signal to noise ratio of ~92 is estimated for quantifying 1 ppm H2O, and for a measurement time of 1 second the minimum detectable concentration is estimated to be about 30 ppb.

The upper limit of the concentration measurements is around 1000 ppm, above this limit uncertainty of the measurement significantly increases due to saturation.

The path length of the cell has been determined using a calibrated laser distance meter to be 36.037 m with an expanded uncertainty of 0.017 m (k = 2).

Gas handling system of the gas cells

Due to the high adsorptivity of water vapour, the measurements will be carried out under continuous flow conditions. The gas samples will be extracted from a humidity generator and forwarded to the gas cell. Flow rates of a few hundred cm3/min will be used. The measurements will be carried out at ambient temperature and pressure, i.e. ~22°C and ~1000 hPa. The gas input ports of the gas cells are equipped with a so called “thermalisation loop”, a 1-2 m long, 4 mm inner diameter stainless steel pipe, which allows the gas sample to take up the ambient temperature before passing through the cell. With the above mentioned flow rates a residence time of a few seconds is achieved in the thermalisation loop, which is sufficient for thermalisation. The pressure of the gas sample will be adjusted by leaving the gas outlet port of the spectrometer open to the atmosphere. The flow rate in the cell will be adjusted by a needle valve placed at the gas inlet port, and measured by a rotameter at the gas outlet port.

For measuring the temperature of the gas sample, Pt100 sensors will be used at the gas inlet and outlet ports in thermal connection with the gas in the cell. Temperatures measured at the inlet and outlet ports will be continuously compared to check that thermal equilibrium is achieved in the spectrometer. If equilibrium is not achieved, the size of the thermalisation loop or the flow rate will be adjusted. According to our preliminary tests under the above mentioned conditions the size of the thermalisation loop is sufficient; the difference in the temperature of the gas sample at the gas inlet and outlet ports is smaller than 0.2 K, which is below the uncertainty of temperature measurements. A pressure gauge with 0-1300 hPa measurement range will be used to measure the gas pressure.

Sensors used for measuring the temperature and pressure of the gas sample will be calibrated to national standards to achieve traceability. According to current calibration certificates, uncertainties of pressure and temperature measurements are in the range of 0.1-0.2 % (k = 2), which is more than an order of magnitude lower than the aimed uncertainty of concentration measurements.

The spectrometer has been built. Currently, it contains the 1.4 µm laser and the 36 m Herriot cell. It is placed inside the home designed purging system to get rid of any parasitic water absorption on the beam path to the gas cell that could affect the spectrometer's performance.

Traceability of the PTB tuneable-diode-laser (TDLAS) hygrometer

The TDLAS hygrometer(s) has been calibrated against the PTB traceable coulometric humidity generator and a transfer humidity standard (Humor 20). The calibration results are presented in (A) and (B) below. Hence, traceability to the SI of the TDLAS H_2O amount fraction results is achieved via the humidity standards. For absol0

ute measurements using the TDLAS hygrometer(s), H_2O line strength values have been measured to address direct traceability to the SI of the H_2O amount fraction results.

(A) Calibration of the TDLAS spectrometer (@1.4 µm) against the PTB Coulometric humidity generator (Between 1-350 ppm)

In Fig.6, TDLAS H2O in N2 results are compared to the coulometric H2O in N2 amount fraction results. The slope value in Fig. 6 is nearly 1 showing a good linearity between the TDLAS results and coulometric results. The TDLAS results in Fig. 6 were calculated using the measured line strength value at 1.4 µm (Deliverable 1.2.2). The standard uncertainties of the TDLAS results in Fig. 6 are in the ±2.4 % range.

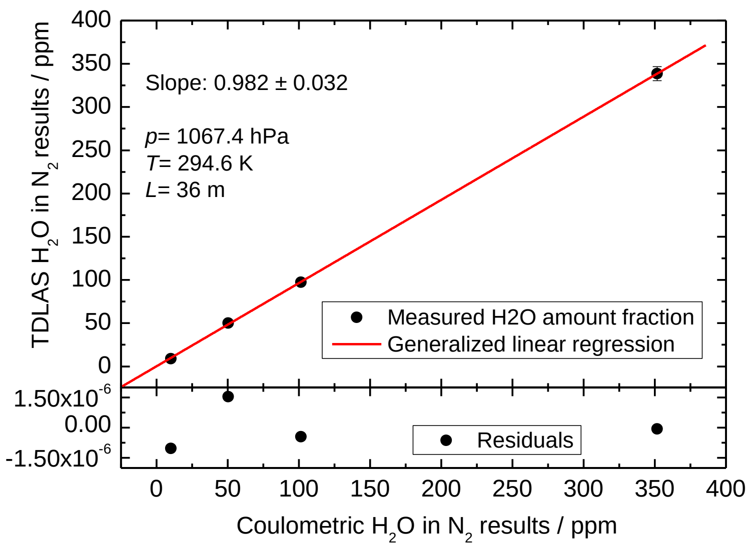


Figure 6: Plot of TDLAS results versus coulometric H_2O in N_2 amount fraction results

(B) Calibration of the TDLAS spectrometer (@2.7 µm) against a transfer standard HUMOR 20 (Between 4000-1800 ppm)

For these measurements, the light source for the measurements presented in (A) was replaced by a 2.7 µm DFB diode laser. In Fig. 7, TDLAS results versus results from a H2O transfer standard (HUMOR 20) are plotted. Similarly as in Fig. 6, the slope in Fig. 7 is nearly unity, indicating a good linearity between the TDLAS results and transfer standard results. The H2O in N2 amount fractions in Fig. 6 were calculated using a measured line strength of a H2O transition at 3619.61 cm-1. The standard uncertainty of the TDLAS results in Fig. 7 is in the ±0.91 % range.

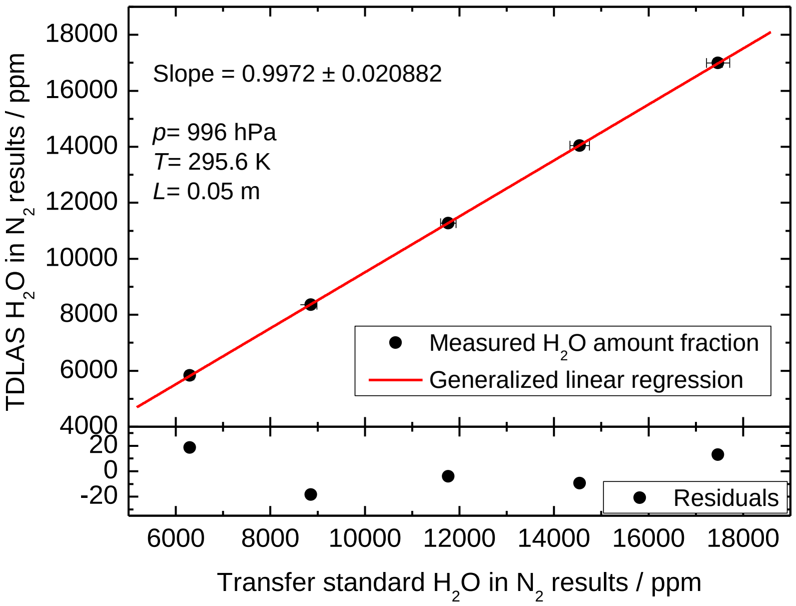


Figure 7: Plot of TDLAS results versus transfer standard HUMOR 20 H2O in N2 amount fraction results

Setup for the measurements at low pressures and low temperatures using modified cells and the traceable spectral line strength data for the PTB laser hygrometer

A modified TDLAS spectrometer has been developed. The setup contains a DFB diode laser emitting at 1.4 µm and a modified gas cell with variable path length (~0.2-5 cm). The gas cell could be used to perform spectrometric measurements at gas pressures less than 1 hPa. The cell is designed such that both the laser light output port and the detectors (Hamamatsu InGaAs photodiode) are sitting inside the gas cell. This design is to avoid light absorption by parasitic water outside the gas cell. The light from the laser to the gas cell is coupled via a single mode fiber. A second cell (path length 20 cm, operation temperature range:-60-90°C) could replace the variable length gas cell for possible further measurements at low temperatures and pressures. A MKS 1 Torr baratron (also available MKS 100 Torr baratron) pressure sensor and a PT100 temperature sensor are used to measure the gas pressure and temperature in the cell, respectively.

The line strength of a water transition at 7299.43 cm-1 (~1.4 µm) was measured using a modified tunable diode laser absorption spectroscopy setup (see D 1.2.1) equipped with distributed feedback diode lasers emitting at 1.4 µm. Here, a 20 cm gas cell whose path length is traceable to the SI was used. The water vapour pressure and temperatures were measured with sensors calibrated against the respective PTB standards. Table 1 holds results for the water line strength at 1.4 µm.

Wavelength / µm	Wave number / cm^{-1}	Line strength / $cm^{-1}/cm^{-2}\cdot$molecule	Combined uncertainty (k = 1)
1.4	7299.43	1.025×10^{-20}	1.72 %

Table 1: Results of water line strength

Self and air broadening coefficients and their temperature dependence have been measured for the PTB hygrometer operating at 1.4 µm. The measurements were done using the modified version of the TDLAS hygrometer(s). Table 2 holds the values of the broadening coefficients and their temperature dependence.

Wave length	Wave number	Coefficient	Value	Relative combined uncertainty
1.4 µm	7299.43 cm^{-1}	γ_{self}	0.43 cm^{-1}/atm	2.8 %
1.4 µm	7299.43 cm^{-1}	γ_{air}	0.1032 cm^{-1}/atm	1.6 %
1.4 µm	7299.43 cm^{-1}	n_{self}	0.701	2.4 %
1.4 µm	7299.43 cm^{-1}	n_{air}	0.75	2.7 %

Table 2: Broadening and temperature dependence coefficients at 1.4 µm

Realisation of a traceable portable calibration facility for hygrometers using permeation tubes

To simplify calibration procedures and to allow field calibration, within the Project a portable humidity standard was developed and realised, which is on the longer term to be further improved to allow field applications. Core elements of the new transfer-standard are different permeation tubes made of synthetic material in a temperature-stabilised water container. A constant rate of water (Strongly dependent on the tube temperature) permeates through the tube wall into a controlled flow of high-purity nitrogen. The water content of the gas mixture can be regulated by the tube and water temperature, the tube length and the flow of nitrogen. Taken as a whole, the permeation source (PS) can prepare gas mixtures with water volume fraction in the low ppm range with an excellent stability. The PS is integrated in a rack and thus can be transported to a required location. It is relatively easily to operate, but requires a nitrogen reservoir and electrical power.

A theoretical calculation of the permeation rate only based on material properties would be nice but in practice leads to insufficient measurement uncertainties, as all commercial tube materials are only incompletely defined and show, due to the admixture of softening agents etc, a quite complex heterogeneous permeation characteristic. This is sometimes the case even if identical material from the same manufacturer is used. To improve the uncertainties of the PS, we directly calibrated the water vapour emission using a reference dew point meter that is calibrated to the national trace humidity standard generator of Germany, whereby, traceability to the SI is ensured.

Figure 8 shows the schematic diagram of the permeation source. The main components can easily be identified in the diagram. Temperature measurements are done at the outlet of each permeation tube (three times) and one additional measurement in the water of the permeation vessel. Pressure is measured as an absolute value at the inlet of the tubes and as differential value as the difference between inlet and outlet of the tubes.

In Figure 9 the calibration measurements are shown. These measurements were taken with a traceable calibrated frost point meter which has been calibrated at the primary coulometric trace humidity generator of PTB.

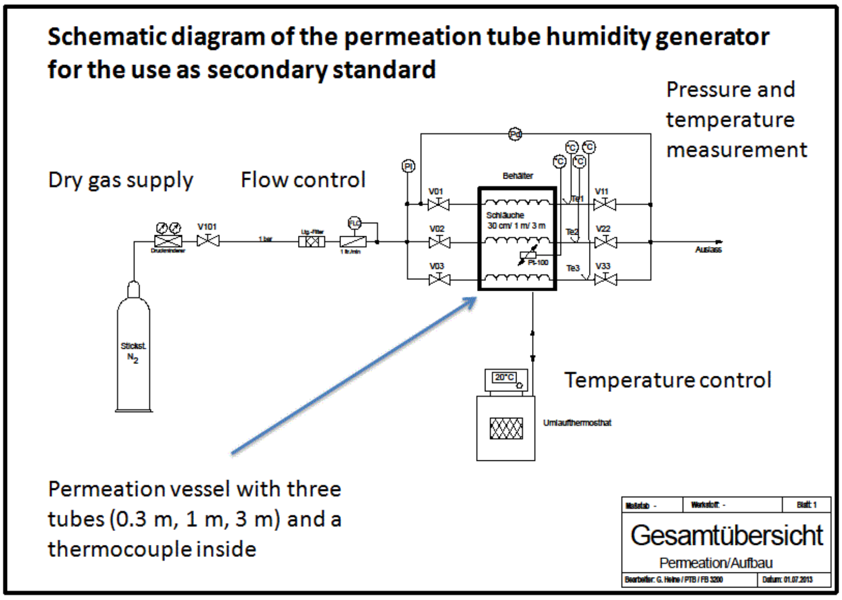


Figure 8: Schematic diagram of the permeation source. The important parts are marked in the diagram

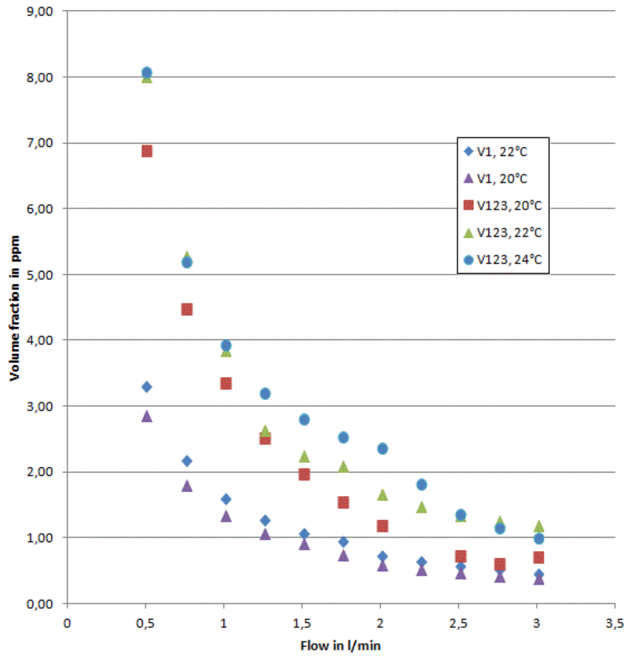


Figure 9: Calibration of the portable permeation source with a traceable calibrated frost point mirror at different temperatures (20 °C, 22 °C and 24 °C) and different tube lengths (V1 one tube, V123 all three tubes in parallel).

Conclusion - Objective achieved: New optical cells for TDLAS hygrometers were developed, and accurate and traceable measurements of the line parameters for the water absorption line were carried out.To simplify calibration procedures and to allow field calibration, a portable humidity standard was developed and realised. The new system will allow for the more accurate in-situ calibration of hygrometers, and traceability to primary measurement standards.

Objective 4: Intercomparison of airborne field humidity sensors of different types (Aquavit 2 campaign)

This inter-comparison was done in April 2013 at KIT and was undertaken by the researcher Dr. Denis Smorgon (REG(KIT)). Water vapour is the most important atmospheric greenhouse gas, which causes a major feedback to global warming and other changes in the climate system. Knowledge of the distribution of water vapour and its climate induced changes is especially important in the upper troposphere and lower stratosphere (UT/LS) where vapour plays a critical role in atmospheric radiative balance, cirrus cloud formation, and photochemistry. But, our understanding of water in the UT/LS is limited, by significant uncertainties in current UT/LS water measurements, particularly in the 2 to 10 ppmV concentration range. One of the most comprehensive inter-comparison campaigns for airborne hygrometers, termed AquaVIT (AV), took place in 2007 at the AIDA (Aerosol Interaction and Dynamics in the Atmosphere) chamber at the Karlsruhe Institute of Technology (KIT) in Germany [1]. One major metrological deficit of AV was, that no traceable reference instrument participated in the inter-comparison experiments and that the calibration procedures of the participating instruments were not monitored or interrogated.

In April 2013 a follow-up inter-comparison was organised, which for the first time also provides a traceable link to the international humidity scale. This AquaVIT2 (AV2) campaign was again located at KIT/AIDA and organised by an international organising committee including KIT, PTB, FZJ and others.

AV2 inter-comparison was divided in two parallel comparisons: 1) AV2-A was a simultaneous comparison of all instruments (incl. sampling and in situ instruments) over a broad range of conditions characteristic for the UT/LS using AIDA; 2) AV2-B, which was the part included in this project (task 1.4), was a sequential comparison of selected hygrometers and (if possible) their reference calibration infrastructure by means of a traceable chilled mirror hygrometer and a commercial two pressure generator acting as a source of water vapour by PTB.

In table 3 a list of the participants in the metrological comparison AV2-B is given. It can be seen from table 3, which instruments operating at which principle and at which range were compared to the traceable calibrated chilled mirror hygrometer together with the stable humidity source. This inter-comparison gives for the first time calibration data to the participants from the atmospheric community on a metrological basis. This is a real added value to the measurements taken in the tropospheric and stratospheric region.

Institute	Instrument	Principle	Meas. Range	Comparison range / Comments
PTB	MBW 373LX TSC3900	CMH 2P-1T Gen.	-95 to +15 °C DP/FP -90 to +10 °C DP/FP	Reference Instruments and generation unit
KIT	MBW 373LX	CMH	-95 to +15 °C DP/FP	1 to 200 ppmV and 100 to 1000 hPa
Univ. Of Szeged	Hilase-Hygro	PAS	0.5 to 50 000 ppmV	1 to 5000 ppmV
UK Met. Office	Spectrasensors WVSS	TDLAS	50 to 60 000 ppmV	1 to 500 ppmV
FAAM/NCAS	Buck CR2	CMH	-75 to +20 °C DP/FP	1 to 500 ppmV at 200 to 1000 hPa
Res. Center Juelich	MBW DP30	CMH	-100 to +20 °C DP/FP	1 to 80 ppmV
DWD	CFH	CMH	-95 to +20 °C DP/FP	10 to 7500 ppmV
University of Colorado	FPH	CMH	-95 to +20 °C DP/FP	5 to 5000 ppmV
KIT	Buck CR2 + PAS	CMH+ PAS	-75 to +20 °C DP/FP -	1 to 200 ppmV and 100 to 1000 hPa
NOAA	RH 373LX	CMH	-95 to +15 °C DP/FP	1 to 500 ppmV and 200 to 1000 hPa
NCAR	Buck CR2	CMH	-75 to +20 °C DP/FP	Instruments failed
Princeton University	RH 373LX	CMH	-95 to +15 °C DP/FP	1 to 300 ppmV

Harvard University	WV-Generator	Mixing Gen.	0.2 to 500 ppmV	5 to 200 ppmV

Table 3: List of participants in the AquaVIT-2 inter-comparison and their instruments, measurement range and comparison range.

Conclusion - Objective achieved: The AquaVIT2, inter-comparison campaign for airborne hygrometers organised in the frame of this project, for the first time involved a significant number of instruments from all main world manufacturers. The result of this study now provides a traceable link to the international humidity scale for this type of sensor adding value to measurements taken in the tropospheric and stratospheric region.

Objective 5: Water vapour formula improvement

The aim of this objective was to perform new measurements of the saturation water vapour pressure in equilibrium over water and ice, to obtain updated data in order to improve the formula for the saturation water vapour pressure.

On the one hand, CETIAT, CNAM and MG performed measurements of the saturated water vapour pressure over water and ice in the temperature range between -80 °C and +100 °C, where vapour pressures lie between 50 mPa and 101 kPa. Two different devices were used to detect and quantify corrections related to possible systematic effects, and to define their impact on the final uncertainty budget: CETIAT and CNAM developed a copper water vapour pressure cell, whilst MG used a stainless steel cell. On the other hand, INRIM investigated the saturation vapour pressure along the sublimation line, in the temperature range from the triple point of water down to 60 °C.

The device developed at CETIAT in cooperation with CNAM was conceived to realise a static measurement of pressure and temperature of a pure water sample in a copper cell, placed inside a closed, temperature-controlled thermostat. The covered temperature range was comprised between 193.15 K and 373.15 K, corresponding to saturation vapour pressure from 0.1 Pa to 105 Pa for the pure water. The vapour pressure was measured by three absolute capacitance manometers (type MKS), with a full-scale pressure of 1 Torr, 100 Torr, and 1000 Torr with an external thermalisation. The measurement of the equilibrium temperature was made with Goodrich capsule-type standard platinum resistance thermometers (CSPRTs), calibrated by CNAM at the highest degree of accuracy.

The device developed at MG consisted of the following components: a calibration bath, in which stainless steel experimental cell was immersed; one pressure transducer (capacitive diaphragm) to measure the vapour pressure; a platinum resistance thermometer (PRT) to measure the sample temperature; a turbomolecular pump to maintain a high level of vacuum inside the system. Pump, experimental cell and manometer were connected by means of ultra-high vacuum fittings. The pressure gauge was a differential manometer, with one side kept at a very low pressure and the other connected to the experimental cell.

INRIM device was composed of: a calibration bath, in which a Pyrex sample cell was immersed; a platinum resistance thermometer (SPRT) to measure the sample temperature; a turbomolecular pump to maintain a high level of vacuum inside the system; two capacitive diaphragm pressure gauges to measure the vapour pressure. The sample cell was cylindrically shaped with a terminating bulb. The bulb was filled partially with a very little amount (about 1 ml) of distilled water, taken from a commercial ultra-pure water source, which ensured to reach a high level of water purity. The aim was to increase the probability to keep water at a super-cooled state at temperatures well below 273.15 K.

Pictures of the three water vapour pressure systems are shown in Figure 10

Water vapour pressure measurements realised in this project were compared to the reference equation determined in 1975 by Wexler, adapted to the International Temperature Scale of 1990 by Sonntag. The plots in Figure 11 show relative differences between experimental data and Wexler's equation modified by Sonntag.

The results obtained with the three experiments are very close to Wexler's equation (modified by Sonntag). This leads to provide new recent data set and uncertainty analysis defined according to the "Guide to the

Expression of Uncertainty in Measurement” (JCGM 100:2008) approach. As there is not strong deviation between data set and reference equation, no new equations are relevant consequently to this work.

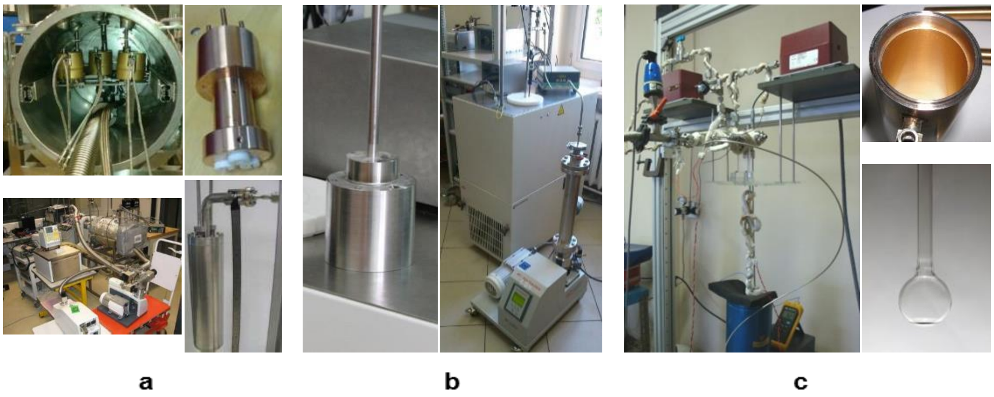


Figure 10: Water vapour pressure systems developed by: a) CETIAT and CNAM; b) MG; c) INRIM

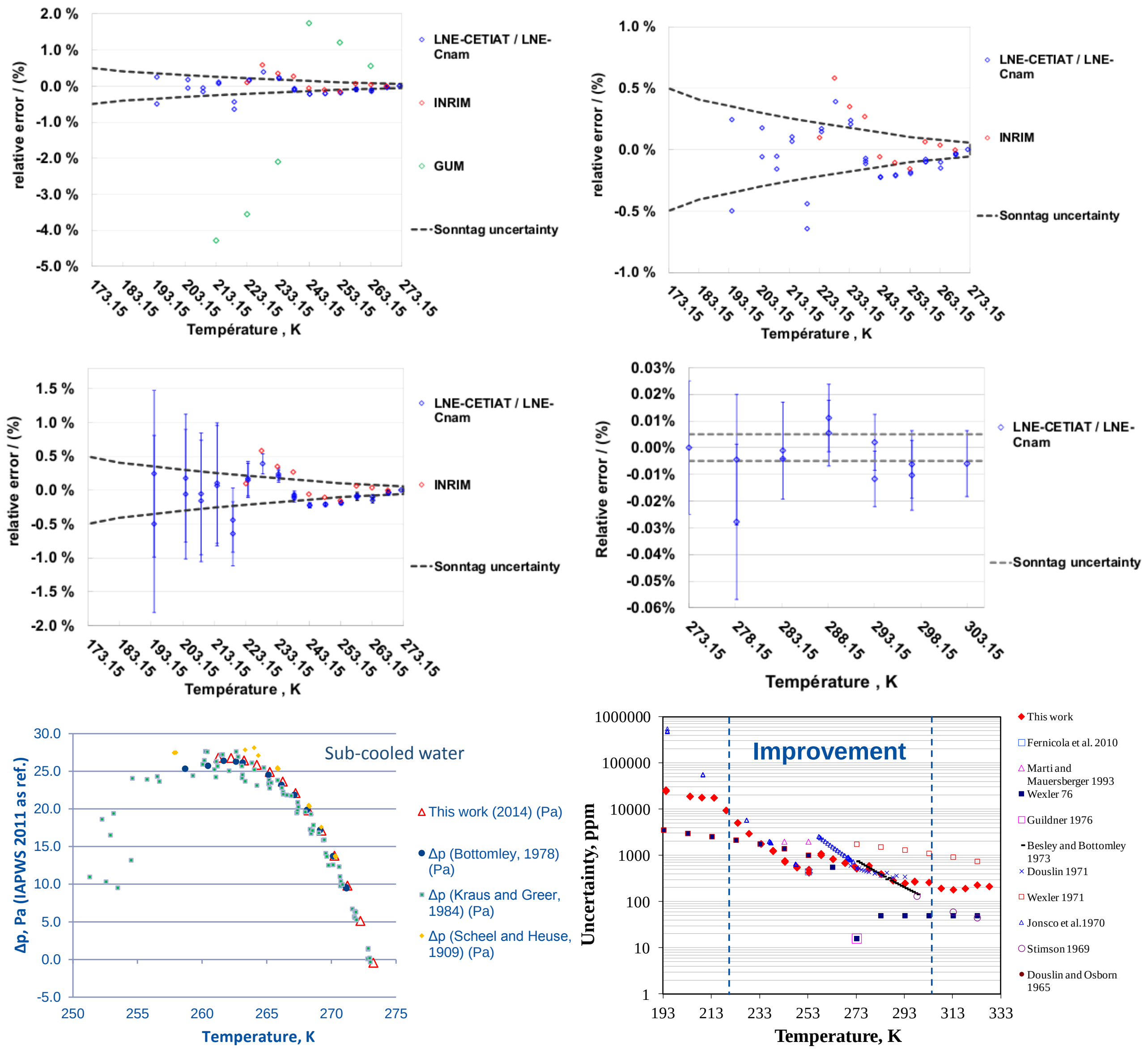


Figure 11: Relative differences between experimental data measured in this JRP and reference Wexler's equation modified by Sonntag. Graph at bottom left shows measurements on sub-cooled water. Graph at bottom right shows uncertainties.

Conclusion - Objective achieved: Data from the new measurements of the saturation water vapour pressure in equilibrium over water and ice, obtained by 3 independent experiments, confirmed the validity of the current water vapour formula.

Objective 6: Novel methods and instruments for atmospheric humidity measurement. Implementation of new hygrometers based on microwave resonances in quasi-spherical cavities, innovative multisensors for free-space non-contact atmospheric measurements, novel methods for GPS and Galileo-based measurements.

The aim of this objective was to develop a new generation of compact, robust and high-sensitivity **hygrometers, based on microwave quasi-spherical resonant cavities**, with target relative measurement uncertainties at the level of 10^{-5}.

The differential microwave hygrometer (DMWH) measures the polarisability change in a moist gas with respect to the same gas devoid of humidity. The change is proportional to the shift of resonance frequencies in a microwave resonator filled with moist gas, with respect to another nearly identical resonator filled by the same dry gas. Differential measurements remove any dependence from gas pressure and temperature. This technique also offers the possibility to check if water condenses on the inner surface of the sphere, by measuring selected TE and TM microwave modes

Two generations of differential microwave hygrometers were realised at CNAM. The first generation was built with two copper quasi-spherical resonators that were used for the Boltzmann constant determination experiment, namely BCU1 and TCU1. The second hygrometer generation was built to overcome the problems of poor thermal stability of the first one, and to reduce the overall size. Two identical copper resonators were realised, designed specifically for the determination of water content in humid gas mixtures. The resonators BCU1 and TCU1 had an inner volume of 523.6 cm^3 but two different masses; conversely the volume of the spheres of the second hygrometer generation was about 65.6 cm^3 and they were realised both with the same mass. Depending on the different dimensions of theses spheres, two different experimental setups were developed. Figure 12 shows the second generation hygrometers and their associated experimental setup.

CNAM, in cooperation with CETIAT, developed a test humidity generator composed of two gas lines, able to produce moisture content between 100 ppmv and 1×10^4 ppmv. Gas lines were equipped with two cold traps, to additionally determine water concentration with a gravimetric method and validate the measurements performed with microwave hygrometers. A dedicated system for microwave signal generation and measurement was developed and characterised. It uses a robust and rapid frequency-locking technique, based on a modified version of the Drever-Pound-Hall technique, and is able to follow sudden changes of the frequency in only few seconds.

Measurements were carried out at low and high water-vapour concentrations in air. At low water-vapour concentration of few parts per million in volume, the differential microwave hygrometer was able to measure a water concentration step of 100 ppmv, followed by a step of about 6000 ppmv and then followed by a step of 200 ppmv. At high water-vapour concentration, the hygrometer was able to measure the moisture evolutions of the laboratory during more than ten hours and with a better time response than a commercial high-quality hygrometer. Results are shown in Figure 13.

In this work, the following objectives were attained:

1. demonstrate the potential of the apparatus to perform an absolute measurement of moisture in air;
2. show the ability of detecting traces of liquid on the inner resonator surface;
3. demonstrate the robustness of the detection method, since frequencies can potentially remain locked indefinitely;
4. show that, by reducing the size of the resonators, the quality of the signal was improved: this opens the way to further volume reductions.

As next steps, to be carried out in the framework of MeteoMet2, a metrological characterisation of the hygrometer will be performed using the high-accuracy humidity generator developed by CETIAT

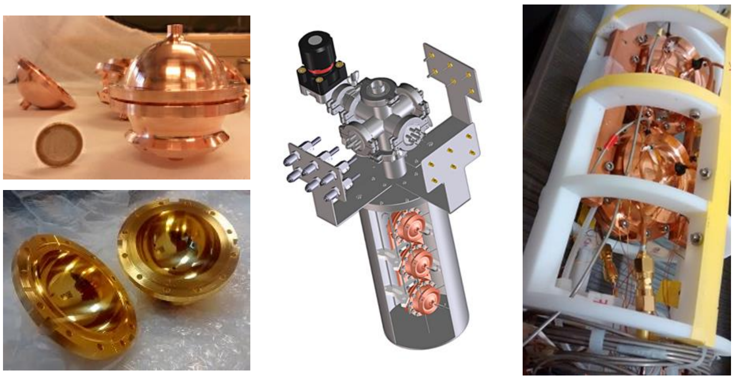
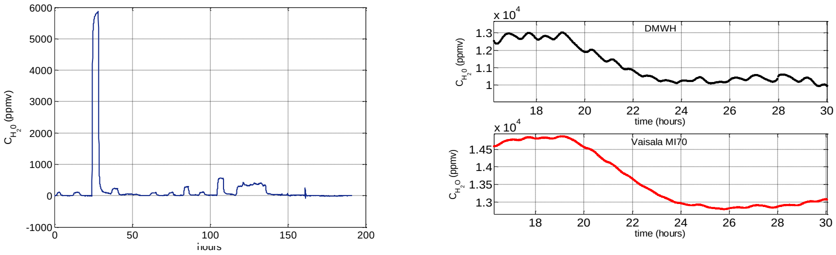


Figure 12: second generation of microwave hygrometers and their assembly



a **b**

Figure 13: measurements with differential microwave hygrometer at a) low water vapour concentration, b) high water vapour concentration.

Novel atmospheric multi-sensors

The aim of this task was to develop free-space non-contact multi-parameter atmospheric measurement sensors and techniques, to enable rapid simultaneous measurements of temperature, pressure and relative humidity of the same air mass, whilst reducing the influence of the sensors themselves on the measurements.

NPL developed a free-space acoustic thermometer and water vapour spectrometer, to measure together temperature and humidity in the same airspace, along with pressure measurement. Tests were completed in the Planetary Environment Facility at Århus University, and in NPL facilities. Successful operation was demonstrated through almost all of the specified test ranges, only limited by the influence of high airspeeds on the speed of sound.

Figure 14 shows some pictures of the atmospheric multi-sensor developed at NPL. Figure 15 shows measurement results

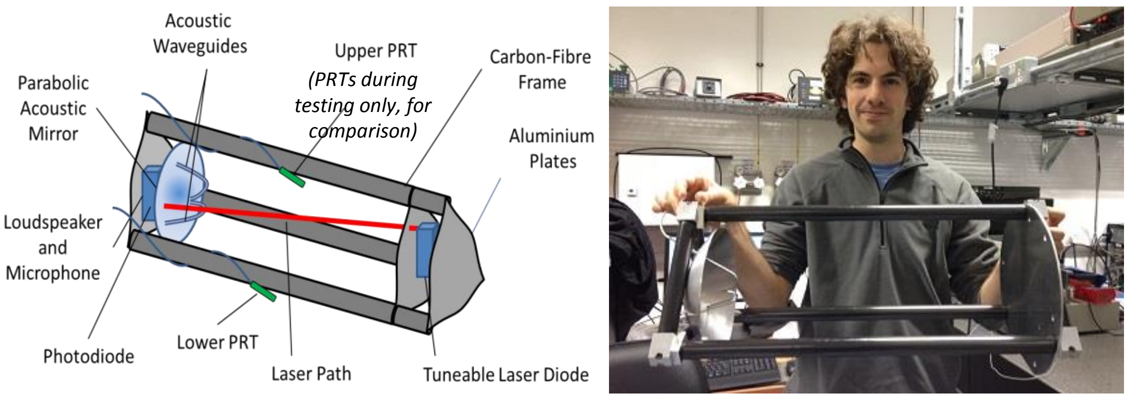


Figure 14: atmospheric multi-sensor developed at NPL

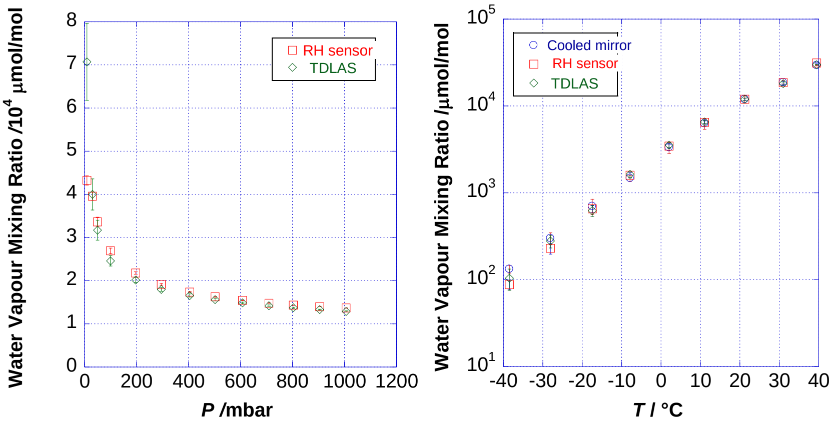


Figure 15: measurement results

GPS and Galileo based measurements

The aim of this task was to develop and implement models for water vapour concentration and temperature profile measurements based on the signals from GNSS (Global Navigation Satellite Systems), such as GPS and Galileo.

GNSS signals can be used for measuring the atmospheric water vapour. On a ground-based approach, permanently installed GNSS receivers are used. In the case of GNSS receivers on-board satellites, vertical profiles of atmospheric temperature, pressure, and water vapour can be determined. SP and Chalmers developed and implemented new models describing GNSS electromagnetic signals that have propagated through the atmosphere, to determine tailor-made strategies for measuring atmospheric water vapour.

Using ground-based GNSS receiver networks (Figure 16) it is possible to determine the Integrated Water Vapour (IWV) in the atmosphere, from a fractional phase φ:

$$\varphi = \rho/\lambda + N + f\left(\delta t^s + \delta t^r\right) + \ell_o + \ell_i + \ell_t + \mu + \varepsilon$$

where λ is the signal wavelength, ρ is the calculated geometrical distance between receiver and satellite, N is the integer number of cycles (ambiguity parameter) and f the signal frequency. δt^s and δt^r represent satellite and receiver clock errors respectively, ℓ_o is the signal error due to errors in the reported satellite orbital model, ℓ_t is the signal delay in the low atmosphere, ℓ_i is the signal delay in the ionosphere, μ is signal multipath, and ε is receiver measurement error.

SP and Chalmers identified the effects that are of importance when estimating water vapour from GNSS signals. They are briefly summarised in the following list:

1. *Reference Frames*: the choice of reference frames shall be consistent between all satellite systems used and receiver antenna locations;
2. *Satellite Phase Patterns*: it is recommended to use satellites with phase center models from the IGS based on estimation from several years' long timeseries;
3. *Ionosphere*: unmodelled ionospheric effects of higher order are not a significant error source that needs to be taken care of;
4. *Multipath*: horizontal error centering of the antenna of the order of a few centimeters does not affect the estimated amount of water vapour. However, absorbent material during and just adjacent to the antenna affects the estimated the amount of water vapour in the percentage level.

Concerning satellite-based measurements, GNSS occultation measurements are considered a powerful tool for detecting climate trends. They are obtained by deploying GNSS receivers onboard Low Earth Orbit satellites (Figure 16), to observe the Doppler shift of the received signal phase and infer the vertical profile of the refractive index, in order to estimate temperature, pressure, and water vapour amount in the atmosphere.

SP and Chalmers identified the main uncertainty sources in satellite-based measurements, as briefly summarised here:

1. *Horizontal Stratification*: it is an important error source in the troposphere. At altitudes between 7 km and 20 km there is essentially no temperature bias. Errors are most pronounced below 7 km heights;
2. *Atmospheric Multipath*: strong gradients in refractive index are caused mainly by water vapour variations, which cause interference of signals. It is recommended to make consistent use of wave optics algorithms for multipath resolution;
3. *Separation of bending angle into pressure, temperature, and humidity*: from the Doppler shift, the bending angle of the signal path can be calculated, to infer a refractive index profile. The refractive index can be modelled as: $N = k_1 \cdot (p\text{-}e) / T + k_2 \cdot e / T + k_3 \cdot e / T^2$, where p is the atmospheric pressure, e is the partial pressure of the water vapour, T is the temperature, k_1 to k_3 are constants.

SP and Chalmers produced a set of quality assured measured atmospheric parameters from GNSS signals for climate models and recommendations on how to determine atmospheric parameters from GNSS signals tailor made for climate research (Figure 17)

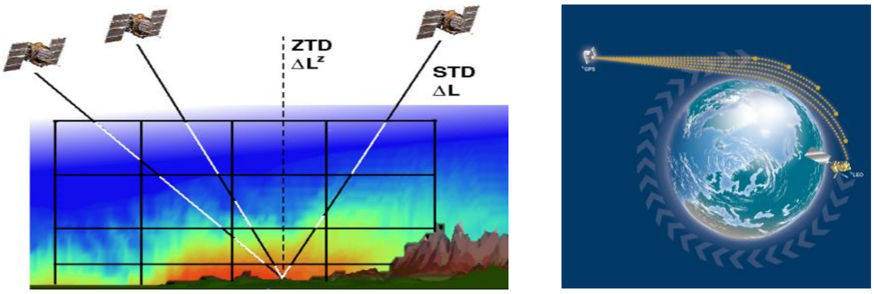


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Figure 16: a) measurements with ground-based GNSS receivers; b) measurements with GNSS receivers aboard satellites

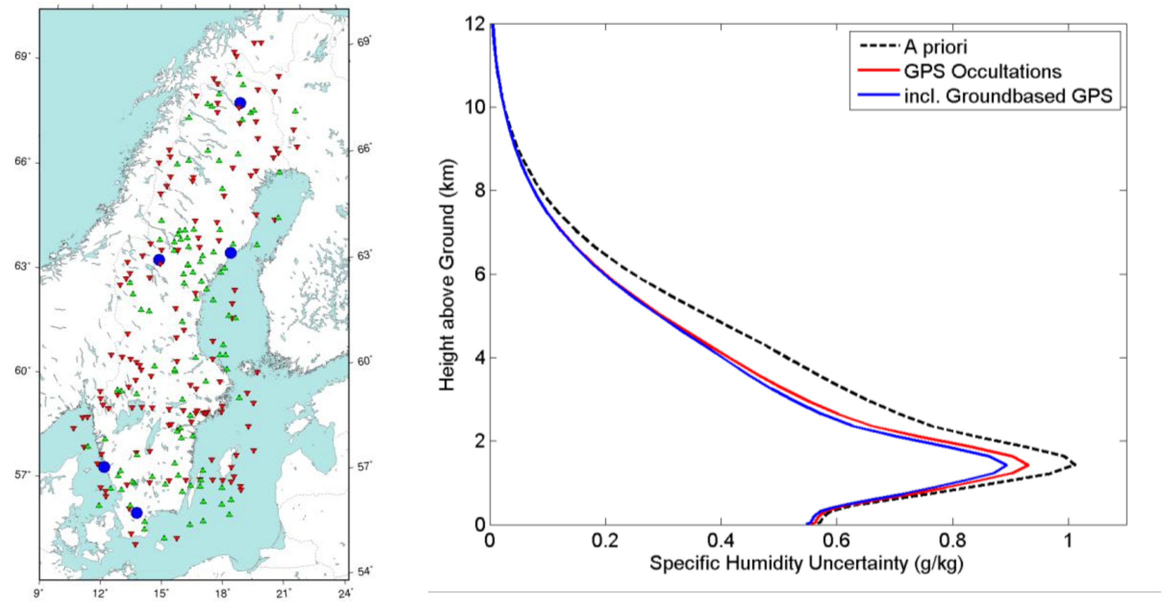

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Figure 17: a) location of GNSS receivers used to generate the set of quality assured data; b) uncertainty assessment of specific humidity profiles using combination of techniques

Conclusion - Objective achieved:

1) A new generation of compact, robust and high-sensitivity **hygrometers** were developed, **based on microwave quasi-spherical resonant cavities**, with target relative measurement uncertainties at the level of 10^{-5}, demonstrating a) the potential to perform absolute measurement of moisture in air; b) the ability to detect traces of liquid; c) the robustness of the detection method; d) the possibility of developing even smaller devices with further volume reductions.

2) **Free-space non-contact multi-parameter atmospheric measurement sensors** and techniques were developed, to enable rapid simultaneous measurements of temperature, pressure and relative humidity of the same air mass, whilst reducing the influence of the sensors themselves on the measurements.

3) Models for water vapour concentration and temperature profile measurements were developed and implemented, based on the signals from GNSS (Global Navigation Satellite Systems) which allowed determination of tailor-made strategies for improved measurements of atmospheric water vapour, and cross validation among different methodologies (satellites, radiosondes, GNSS signals).

3.3 Calibration of reference radiosondes

Objective 7: Development of a novel calibration system comprising a measurement chamber with highly optimised heat and mass transfer characteristics for establishing traceability for radiosonde-based measurements.

Radiosondes are used to obtain upper air weather data needed for climate change studies and weather forecasts. Reference radiosondes are being developed to meet GRUAN accuracy requirements and they will be used at GRUAN reference weather stations around the world. The specified accuracy requirement for water vapour mixing ratio is 2 %. In MeteoMet, MIKES has been developing a humidity calibration facility for radiosondes meeting the GRUAN requirements. The main challenge is fast operation at temperatures down to -80 °C. Vaisala has provided prototypes of new Vaisala reference radiosondes for tests and assisted in operating with them.

The calibration set-up can be seen from figure 18:

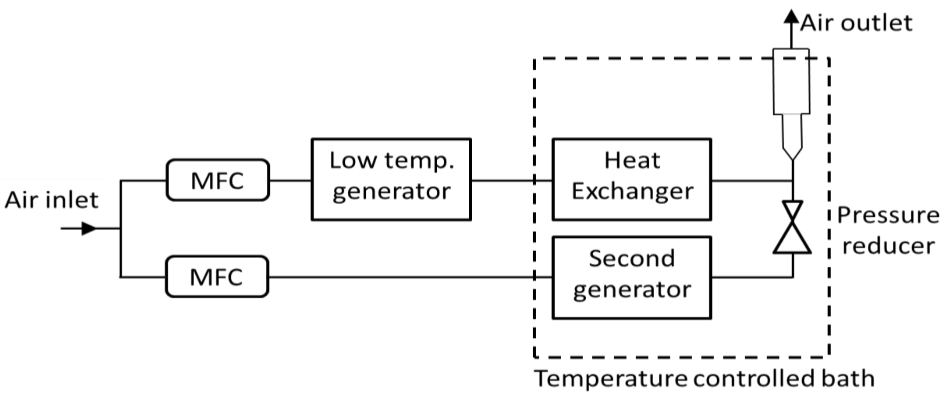

Figure 18: Calibration set-up for the calibration of humidity sensors in radiosondes meeting the GRUAN requirements.

The main features are:

- Dew-point temperature: -90 °C to +10 °C
- Temperature: -80 °C to +10 °C
- Calibration time quick enough for daily calibrations
- Uncertainty level of 2 % achieved

Conclusion - Objective achieved: A novel system for the calibration of radiosondes and reference grade radiosondes was developed, allowing the calibration of those devices in the wide range of temperature and conditions met during the ascent in the troposphere and stratosphere. The uncertainty was reduced with respect to any other existing system and with respect to manufacturer‘s specification. The work met the GRUAN accuracy requirements and was performed in close cooperation with a lead manufacturer of radiosondes.

3.4 Calibration of automatic weather stations (AWSs)

Objective 8: Proposal for calibration methods and protocols for weather stations and evaluation of the effect of solar radiance and ageing on weather stations

In order to develop traceable protocols for temperature, humidity, and pressure ground-based measurements by AWSs a review of the procedures, type of sensors, calibration practices was carried out.
A **database** (https://meteomet.e-science.pl) was prepared by which presents the state of art of weather stations in European countries. It collected the following data:

a) weather station information: owner (country, institute and contact), location, type, amount, type of meteorological parameters observed;
b) sensor employed: manufacturer, type, range of measured parameter, accuracy, ability to dismantling;
c) measurement: frequency, method, software to register data;
d) calibration: frequency, method;

The base contains data obtained from 20 countries. The database is a tool to serve the community of metrologists and meteorologists even after the end of the project. It is open to further complement the data and modifications. It is possible to supplement the data after registration on https://rejestracja.e-science.pl. Since the end of the project a desire to supplement the data reported two more countries. The database is a tool which allows creating all kinds of statistics related to the data. At present are created statistics on the number of AWS and number of sensors in different countries. According to the needs of users, kinds of statistics will be increased.

Moreover a survey of existing procedures for implementation, maintenance and calibration of weather stations was obtained. It received response on prepared **questionnaire** from eight meteorological institutions from: Austria, Ireland, Spain, Turkey, Slovenia, Norway, Serbia and Poland. The questionnaire consisted of two parts. The first part concerned the general information about weather stations used, the second part included questions on the sensor calibration. The obtained data shows that the Meteo Institutes use similar equipment and most of them calibrate sensors at their own accredited laboratories. Most of them have intermediate check procedures too. The calibration for temperature and humidity sensors is for comparison using a climatic chamber and a liquid bath. There are no unified details of calibration method (e.g. calibration with or without shield, the number of calibration points and range of calibration), form of presenting results (table of results or determined characteristics equation) and the interval between calibrations (from 1 to 3 years).

In order to develop procedures for calibration of pressure-temperature-humidity sensors of weather stations INTiBS and MG calibrate the sensors used in weather stations against appropriate reference standards in the laboratory. A group of different types of meteorological sensors, commonly used by the meteorological services, representing different history of work, was selected. To check a real metrological parameters – stability, reproducibility and temperature characteristic – the sensors were tested in laboratory conditions at every 10 °C between -50°C and +50 °C. For the study a typical liquid thermostat bath with a cylindrical copper air chamber was used. The temperature measurements were carried out simultaneously, i.e. at the same time and at the same time intervals by the control PRT and the tested meteorological thermometer. Temperature characteristics of sensors were determined. The reproducibility was examined. The temperature characteristics were not linear what confirms the need for calibration in more than two or three temperature points. The uncertainty budget for measurements was elaborated in accordance with the EA-4/02 document. The sources and types of measurement errors were defined and measurement uncertainty budget was developed. The contribution of individual components of the measurement uncertainty was analyzed. The investigation carried out at the INTiBS, and confirmed by the MG, showed a good reproducibility of metrological parameter of the sensors used in meteorology for temperature measurements. The calibration procedure applied in laboratory condition allowed to reach a small uncertainty of measurements – below 0,1 °C.

The meteorological sensor were tested in a climatic chamber also. The used chamber enabled the temperature change in the range from -40 °C to +50 °C and a humidity from 20% to 90% RH above 10 °C. The measurements have confirmed a lack of relation between the registered temperature and humidity. Also, the tests in the climatic chamber have not changed thermometers metrological characteristics.

The analysis of the results led to the development of “The procedure of meteorological temperature sensors calibration. The basic guidelines" which was sent to the coordinator. Information concerning the calibration of humidity and pressure sensors were prepared by the MG.

Test and calibration results and the conclusions drawn from them are summarised in the report "Meteorological thermometers calibration in the laboratory - the results, problems and challenges". In addition, they have been presented at an international training Metrology for meteorology and Climate (MMC) in Slovenia as well as in the form of an article submitted to the journal Meteorological Application (review and recommended to publication).

MIKES work on the ”Procedures for the combined laboratory calibration of temperature, humidity and pressure sensors in weather stations” with focus in low temperatures down to -52 °C was reported in MCC 2014.

Conventionally each parameter is calibrated separately for multiparameter instruments so possible correlations are not taken into account. This work focused on correlations between pressure, temperature and humidity in automatic weather stations and weather transmitters. The aim was to: analyse if current calibration practices are sufficient as far as the correlations are concerned and propose an amended calibration procedure if needed. The work included analysis of information already available and experiments with a Vaisala WXT520 weather transmitter. The obtained results:

1. No specific correlation issues related to temperature sensors were found
2. Significant temperature dependencies have been found for some barometers but correlations with relative humidity seem to be insignificant. Type test approach may be sufficient for including the dependences in the measurement uncertainty.
3. Often, humidity sensors have significant temperature dependence that is not stable in time. Calibration scheme should at some extent cover the temperature dependence (depending the target uncertainty)
4. Experiments with a WXT520 did not bring up further needs for improving calibration procedures

Recommendations for the calibration procedure to cover the correlations between the three parameters:

- No actions are needed related to the effects between pressure and relative humidity
- No actions are needed related to the effect of pressure and relative humidity on temperature indication
- Effect of temperature on pressure indication:
    1. this should be included in the initial calibration: at least max and min temperature at max and min pressure
    2. regular calibrations can be calibrated to room conditions (although we don’t have enough information about actual stability of the temperature characteristics in long term of barometers used in AWS)
- Effect of temperature on relative humidity reading: at minimum, one relative humidity point should be measured at least 3 temperature points covering the whole temperature range of interest.

Solar radiation effect

In order to evaluate the effect due to solar radiation on climate measurements a new radiation shield model with forced ventilation was designed and constructed by SP during the project. Shields with different coatings (black and white) were tested in sun light from June 21 to July 6 in 2012. The measured temperature difference between black radiation shield and the white shield was in average 0.11 K. In addition, the measured temperature difference depended on the weather conditions: the difference increased with increased solar radiation. The wind speed seemed not to influence the measured temperature difference between the two shields.

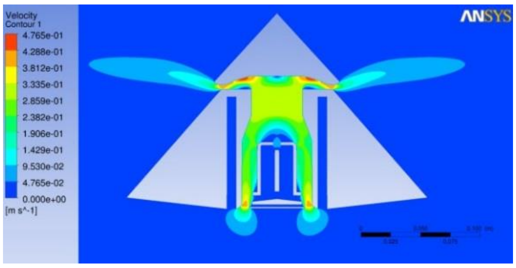

Figure 19 The results from the CFD-simulation performed with Fluent. The results shows that the air is leaving the radiation shield more or less straight out limiting the risk of having the same air circulating through the shield**.**

A long-term investigation consisting of 4 reference shields and 6 other commonly used radiation shields has been performed in the project. Measurements have been done at two different locations, in Sweden by SP and in Spain by INTA. Three models of radiation shields were tested at both locations. For both measurement locations, the radiation shields designed by SP was used as a reference.

From the analyzed measurements in Sweden, from September 2013 to February 2014, in average the measured temperature differences varied from +0.14 K to -0.24 K. In 84 % to 94 % of all the measured temperatures the differences was between -0.5 K to +0.5 K. All radiation shields expect the SP White III (who had no active ventilation) measured in average a higher temperature then the reference radiation shield. At specific times the measured difference could be above 4.9 K.

From the analysed measurements in Spain, from November 2013, in average the measured temperature differences varied from -0.04 K to -0.21 K. In 87 % to 99 % of all the measured temperatures the differences was between -0.5 K to +0.5 K. All radiation shields measured in average a higher temperature then the reference radiation shield. At specific times the measured difference could be above 2.3 K.

It was shown that in the case of 2 screens of the same model but with over a decade difference in exposure to UV, the radiation effects were not enhanced with measurements between the average values of maximum and minimum temperatures only differing by 20 mK, negligible within the uncertainty of measurement.

One objective was to propose a procedure for harmonising the temperature measurement with different radiation shields. For this case the most interesting part to investigate are the commonly used radiation shields. The results for the five commonly used radiation shields that were used in this long-term comparison have been analyzed. It was concluded that in average over a period of time there were small differences for the different shields. However, comparing the results from different locations and also considering the measurement uncertainties, it was not possible to set up robust correction models. The conclusion for proposed harmonisation model for measurement with different radiation shields are that further work and data is needed.
The **radiation shield influence** on the behavior of a selected group of AWS temperature sensors, when they have been exposed at extreme environmental conditions of temperature and humidity in a climate chamber, were analyzed by CEM and examples of such study are shown in figure 20

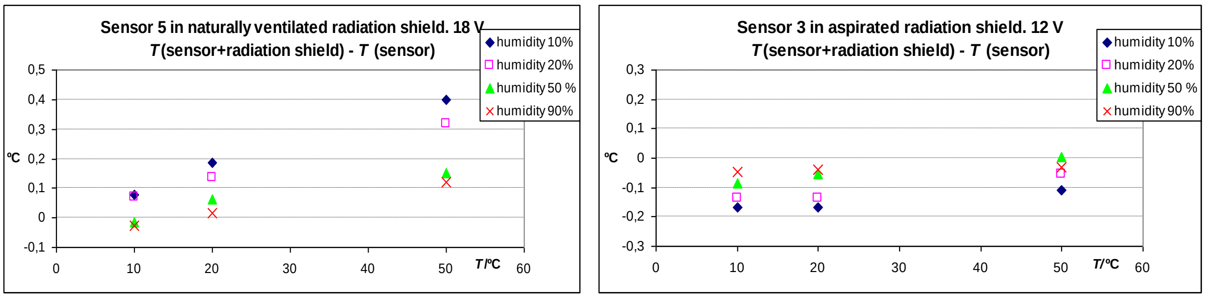

Figure 20. Influence of radiation shield in the calibration of temperature sensors

The influence of radiation shield on temperature measurements depends on the design of the radiation shield.

Radiation shield with plates (naturally ventilated) : The influence increases with temperature and decreases with humidity and as a general rule, the temperature measured by the sensor is higher when is inside radiation shield.

Aspirated radiation shield: the temperature measured by the sensor is lower when is inside the radiation shield and the influence decreased with temperature and with humidity.

The performance of a selected group of temperature sensors under extreme conditions of wind and salinity was analyzed.

Extreme conditions of wind:

The relative performance of a selected set of temperature, relative humidity and pressure sensors installed in different radiation shields, were studied at INTA under different conditions of wind, 3 m/s to 40 m/s, at ambient temperature in a wind tunnel.

Salinity effect

The ageing of some temperature sensors with salinity were studied by the drift of the thermometers reading at 20 ºC in a liquid bath, after some time of exposure a salinity environment. This condition was produced in a salinity chamber with the parameters in agreement with the standard ISO 9227:2006(E).

Test method: Neutral salt spray (NSS)	
Concentration of sodium chloride (collected solution)	50 g/l ± 5 g/l
Temperature of salinity fog	35 ºC ± 2 ºC

The measurements are shown in figure 21. One of the sensors broke during the essay due to the failure of the internal electronic of such sensor

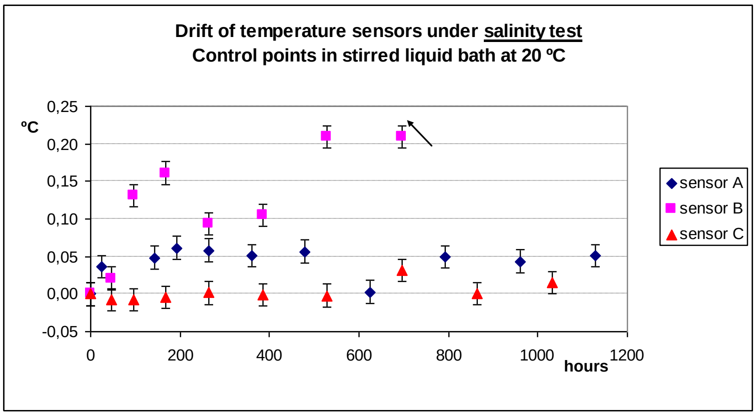

Figure 21. Ageing of temperature sensors after exposing to salinity fog

Conclusion – Objective achieved
1) A database (https://meteomet.e-science.pl) was prepared to collect knowledge about the multitude of weather stations in European countries, including existing procedures for implementation, maintenance and calibration. Such a collection of data was missing and brings valuable information on the comparability of data from different weather services, for climate studies and for future actions toward the definition of European reference standards.
2) A new radiation shield model with forced ventilation was designed and constructed in two different models: one with black shield, the other with white reflecting painting. This solution was adopted to evaluate the maximum difference due to heat transfer from solar radiation. The screens were compared with other representative solar shields both in cold and snow covered areas and in warm desert-like conditions. The white shield showed better performance with respect to the existing models and the maximum difference with respect to the black one was limited to 0.11 °C
3) The drift of a group of temperature sensors due to exposure to salinity was studied in a chamber accelerating the effect and simulating a multi-year exposure of sensors in sea areas. The results made possible the evaluation of this effect in terms of a contribution to the uncertainty in temperature measurements in such areas.

Objective 9: Development of facilities for laboratory and in situ simultaneous calibration of temperature, humidity and pressure sensors in weather stations, including those operating under extreme environmental conditions.

To obtain more accurate AWS calibration results a new in situ calibration system, named EDIE (Earth Dynamics Investigation Experiment), with simultaneous and independent control of pressure, temperature, and humidity was developed at INRiM (figure 22). The chamber is equipped with reference sensors directly traceable to national standards to obtain meteorological data to guarantee well documented calibration uncertainty.
This apparatus is designed to allow the complete characterisation of the whole AWS pressure-temperature-humidity modulus. In fact, the humidity generator allows the hygrometers calibrations in temperature and pressure variable conditions and the calibration of thermometers and barometers under different humidity values as quantity of influence.
EDIE allows to perform temperature calibrations in air, instead of in bath, in order to simulate the real working conditions and characterise the sensor response more accurately.

A characteristic of this facility is its ability to cover a wide range of atmospheric variability with one media. The temperature is controlled between -25 °C and +50 °C and the pressure between 50 kPa and 110 kPa. The target uncertainty (k=2) of pressure and temperature are 10 Pa and 0.076 °C.
The humidity control is obtained by a dedicated small saturator placed on the external part of the chamber and the traceability guaranteed by a standard hygrometer directly traceable to national primary standard. The humid gas generator is based on a single-pass isothermal saturator and is targeted to generate dew/frost point temperatures between -25 °C and 50 °C (depending on ambient temperature) at any constant pressure between 85 kPa and 120 kPa. The reference relative humidity is calculated by means of the dew/frost point temperature as measured by a reference chilled-mirror hygrometer and the air temperature as measured with a reference platinum resistance thermometer inside the EDIE chamber.
One of the big advantages of this apparatus is its reduced dimensions. The good compromise between measuring inner chamber (inner diameter 220 mm and volume of among 15 l) and external total dimensions (350 mm x 650 mm) makes it transportable for in-situ calibration campaigns but at the same time can hold the whole sensor and dataloger. In this manner, the whole measurement chain can be tested in working conditions to reduce further calibration uncertainty contributions due to the datalogger, the ADC conversion, and the software elaboration.
The use of this new chamber allows a comparison against national standards also for these AWSs installed in remote area where the difficulties to access delay or forbid periodic calibrations. During the project EDIE calibration chamber was used for two calibration campaigns in extreme environmental conditions:

- in the Ny Alesund research site, in the polar area where a GRUAN (Global Climate Observing System (GCOS) Reference Upper Air Network) station is hosted. The work has been devoted to the calibration of those pressure and temperature measuring instruments used as ground check for the radiosondes sensors just before launch.
- in the Ev-K2-CNR Pyramid-laboratory in Khumbu Valley at 5050 m of altitude in the Nepalese side of Hymalaya, close to the Everest base camp. An ad-hoc calibration chamber, named EDIE2, have been manufactured. This chamber is similar to EDIE1 but can be split in light weight components to be delivered by human porters, Sherpas. On September 2013 the climatic chamber was installed in the Pyramid laboratory by INRiM staff, and the calibration campaign of the AWS in use in the whole valley was carried out.

Figure 22: EDIE1 climatic chamber with and without covers

A second facility (called EDDIE – Earth Dynamics Direct Investigation Experiment in figure 23) has been realised at INRIM in order to perform several laboratory tests on weather stations. The facility consists in a closed tunnel that can generate the following environmental conditions: air pressure range from about 75 kPa to 110 kPa, air temperature range from about -40 °C to 40 °C and airspeed range from 0 m s-1 to about 30 ms-1. One of the relevant characteristics of EDDIE consists in the test chamber, which is equipped with a device (called shield system) that will allow to evaluate the instrument behavior in a specific condition of temperature and pressure both in absence and in presence of wind. The multi controls (air velocity, temperature, pressure and humidity) have been obtained through the assembly of three different modules into a complete system. The first module is composed by the air circuit for wind simulation at different climatic conditions. The second module consists in a dehumidification system for the dehumidification of the air contained in the test circuit. Module 2 is necessary to reach extreme air temperature conditions, without damaging the motion part of the circuit and maintaining the optimal conditions for the refrigerator device operation avoiding condensation or ice formation on the exchanging parts. Module 2 has been planned to also set the ambient pressure inside the air circuit. The third module consists in a refrigerator system that allows the air temperature conditioning inside the circuit. Module 3 is a complex system that controls a chiller and a heating coil placed inside the air circuit. The system exchanges heat also with external ambient thanks to two axial fans placed outside the laboratory building.

Figure 23: The EDDIE facility at INRiM

Conclusion - Objective achieved: Two systems for the calibration and characterisation of automatic weather stations and thermometers were produced.

a) A new **in situ calibration system**, named **EDIE** (Earth Dynamics Investigation Experiment), with simultaneous and independent control of pressure, temperature, and humidity was developed. One of the big advantages of this apparatus is its reduced dimensions which make it useful also for calibration of AWSs installed in remote areas where periodic calibrations are delayed or forbidden. Uncertainties in the calibration are well within the values obtained in normal laboratory calibration procedures. During the project the EDIE was used for two calibration campaigns in extreme environmental conditions: at the Ny-Ålesund research site, in the Arctic area, and at the Ev-K2-CNR Pyramid-laboratory in the Khumbu Valley at 5050 m of altitude in the Nepalese side of Himalaya. The Ny-Ålesund campaign is now a case study of Euramet impact contribution.

b) A second facility (called EDDIE – Earth Dynamics Direct Investigation Experiment) has been realised to perform several laboratory tests on AWSs. The facility consists in a closed wind tunnel that can control air pressure, temperature, and wind. No such system was available before and this device will allow full characterisation of weather instruments, with long lasting tests at a wide range of conditions. Its use was booked immediately at the end of its construction.

Objective 10: Development of protocols for software validation of automatic weather stations

A questionnaire was distributed among European and non-European meteo services, asking them about their view on the key performance characteristics of automatic weather stations. Based on the overwhelming response from 25 countries results were analysed using Quality function deployment tool. They were presented at the first International workshop on Metrology for Meteorology and Climate, MMC 2014 and submitted to journal Meteorological Applications for publication. Additionally, validation tests of data-logging software used in AWSs was performed, using access to the AWS broad sensor network of collaborator Slovenian Environment Agency (ARSO). The validation was based on the assessment of the need for validation in the scope of task 3.1. The results of the validation were also presented at MMC 2014.

Conclusion - Objective achieved: A quality function deployment analysis was made on the results of a questionnaire distributed among European and non-European meteorological services about the key characteristics of AWSs. The result showed a satisfactory level of quality in the use of such systems, with possible improvements in data traceability. A validation test of data-logging software used in AWSs was performed, demonstrating good state of the art with respect to the required accuracy of such systems.

3.5 Robustness of the historical temperature measurement data

The aim of this objective was to investigate sources of uncertainty in historical temperature data, include them into the uncertainty budget and correct the input to the climate models thus enhancing climate change detection, prediction and adaptation assessments. A novel software based model for the harmonisation of data under such a metrological approach was developed.

Objective 11: Assessment of the historical temperature measurement data with respect to the techniques used (procedures and instruments) and evaluation of the consistency of contemporary and historical data.

This project has collected a total of 99 series from five different countries. The data and the metadata were fed into a **database** that was developed in MS Access prior to further analysis. This database is designed with the potential to include additional data series later. Of the 99 series, two series from Norway, two from Italy, 22 from Spain and one from Czech Republic were received within the data collection deadline. A further attempt at collecting data was made by contacting metrological institutes directly. This resulted in 72 series from Germany.

An example of a diagram of historical mean air temperature data by month is shown in figure 24. The data represented here is taken from four data series in different countries at a random period of 5 years. This data is calculated in a query from the database (figure 25).

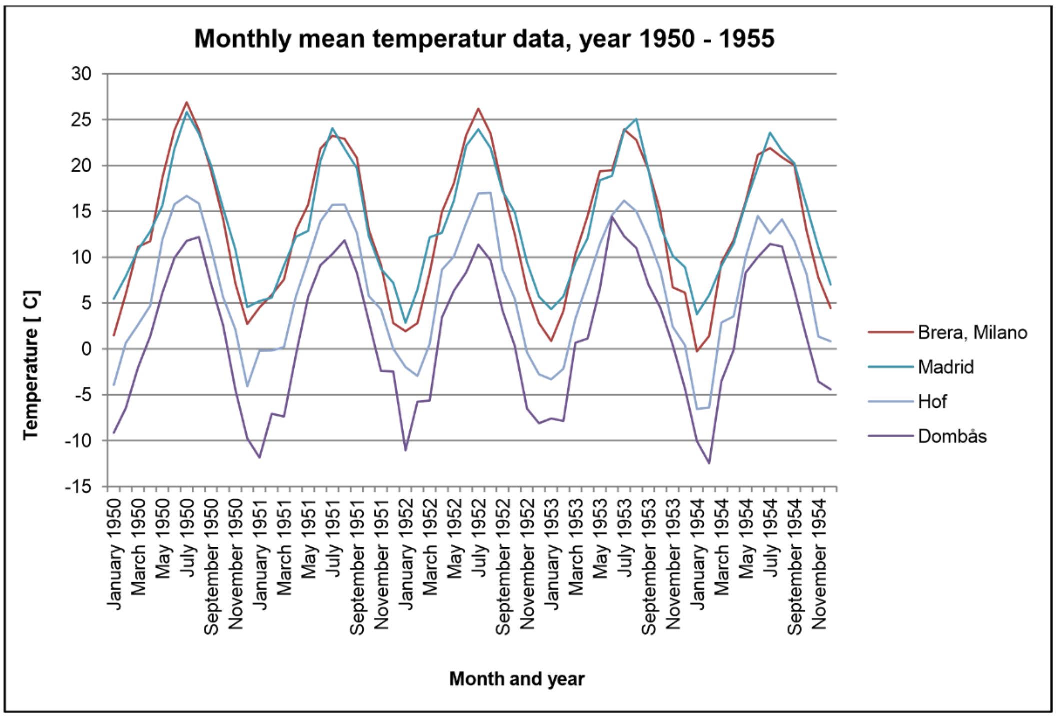

Figure 24. Monthly averages of mean temperatures, from 4 different series, in the period 1950 – 1955.

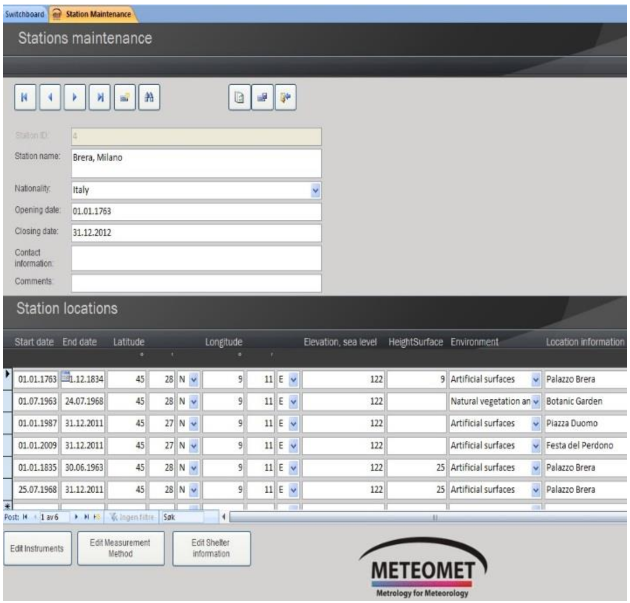

Figure 25. Look of the database.

To analyse a long term air temperature series, it is important to have knowledge of the relevant metadata and how the measurements were taken. From a metrological point of view it is virtually impossible to identify or disseminate trends from the data without any metadata.

Knowledge of the type of the sensor used for the temperature measurement provides very valuable information for uncertainty budget creation. A short **review of the most widely used instruments** was carried out and for each type of instruments, separate uncertainty budgets have been created. Between sources common to every type of the instrument there are:

1. *Calibration of the instrument* - to check, if the instrument still shows correct values, and what correction have to be applied, serves calibration. Knowledge of the uncertainty of the calibration represents one of the fundamental uncertainty sources. Unfortunately, most of the received data didn't provide any information, if the instruments were calibrated and what was the period. Based on this fact, value of this source had been estimated on the basis of the experience from the calibration work at temperature laboratory.

2. *Drift of the instrument* - describes the behaviour of the instrument between two checks of the instrument or between two calibrations. Most easily exact value of this source can be determined by comparison results of the calibrations. Because no information about the calibrations was known, value of this source of the uncertainty had been estimated according to experience from the calibration work at temperature laboratory.

3. *Resolution of the instrument* - is one of the basic sources of the uncertainty. Into the created budget it enters as a value calculated as a half of the smallest division on the scale. In available database, some series form the Italy and Norway provided this type of information, for other series was this value estimated based on knowledge of the type of the instrument, experiences and according to the available data.

4. *Errors of the instrument* - all thermometers are technical devices; therefore some mechanical troubles could happen during the time of the instrument usage. Hysteresis can influence measurements of the thermometers contained metal particles, in case of the thermo(hygro)graphs inaccuracies due to dry ink can be presented in the data.

5. *Observation (human) effect* - especially in the past, when reading of the thermometer was done personally by a human, observation mistake could be done. Several reasons can lead to the errors. Temperature had to be deducted at the same time, but sometimes the person doing the reading of the values could be late, or record the wrong value. Size of this source of the uncertainty has been determined as a one division on the scale. This source has a big influence on the measurement, where

automatic recording of the value is not possible, mostly in usage of the liquid-in-glass thermometers, or evaluation of the data came from thermo(hygro)graph.

6. *Application effect* - for the measurements under the objective conditions, measured devices should be placed in a space, which is protected before direct sunshine or wind. That's the reason, why instruments should be placed in some shelter, which prevents instrument against these influences. Also, location of the sensor installation can influence measured value. Sensor located in the urbanisation (e.g. between buildings) can be influenced by the radiation coming from the walls of the building during the summer.

As an example, two uncertainty budgets for historical data series are shown (new equipment and old one).

Table 4: Uncertainty budget for the data measured at 1785 with mercury thermometer

Source of uncertainty	z_{max}		**distribution**	**uy**	
thermometer					
Calibration of the thermometer	1	°C	normal	0,5	°C
drift of the thermometer	0	division	rectangular	0	°C
resolution of the thermometer	0,125	°C	rectangular	0,072168784	°C
Errors of the instrument	1,00	division	rectangular	0,144337567	°C
other sources					
Human error	0,125	°C	rectangular	0,072168784	°C
Application error	2	division	rectangular	0,288675135	°C
Combined standard uncertainty (°C)				**0,603807364**	°C
Coverage factor				2	
Uc round (°C)				**1,2**	°C

Table 5: Uncertainty budget for the data measured at 1834 with mercury thermometer

Source of uncertainty	z_{max}		**distribution**	**uy**	
thermometer					
Calibration of the thermometer	1	°C	normal	0,5	°C
drift of the thermometer	5	division	rectangular	0,721687836	°C
resolution of the thermometer	0,125	°C	rectangular	0,072168784	°C
Errors of the instrument	1,00	division	rectangular	0,144337567	°C
other sources					
Human error	0,125	°C	rectangular	0,072168784	°C
Application error	2	division	rectangular	0,288675135	°C
Combined standard uncertainty (°C)				**0,940965816**	°C
Coverage factor				2	
Uc round (°C)				**1,9**	°C

- Development of methods and software to take into account inhomogeneities in historical data measurement including B-Type uncertainties.

Prior to the 20th century a further complication is the fact that no universally accepted temperature scale was available. The earliest internationally accepted scale came into force after the first CGPM (Conférence Général des Poids et Measures) in 1889, but its dissemination and use was limited to scientific purposes. Only from

1927 was there a widely accepted and internationally recognised temperature scale available. A reconstruction of historical records therefore involves transforming measurements from one of the various historic scales to the modern Celsius scale. To further exacerbate the problem even the Celsius scale used in some historical records was not necessarily the same scale as familiar to us today: its seemingly well defined fixed points at the freezing and boiling points of water, are only truly fixed under judiciously controlled conditions.

The modern thermodynamic temperature scale was established in 1954 as a specified gradation between the absolute zero and the triple point of water (at 0.01 °C), in line with a suggestion from Lord Kelvin more than a century earlier. However, this formal definition of temperature is not amenable to a practical implementation: in consequence the practical realisation of the temperature scale remains to this day rooted in the same basic ideas as used in historical scales. The idea comprises three essential components: (i) a series of phase transitions to act as fixed points, today metal and noble gas phase transitions under tightly controlled conditions; (ii) an interpolating instrument used to realise the scale between the fixed points; and (iii) an empirical mathematical equation relating temperature to the instrument response (typically electrical resistance). But neither of the three components are unique, and during the past century the scale has been revised several times by adjusting the temperature assigned to the phase transitions, adding or removing phase transitions from the list of fixed points, or changing the reference instruments.

A **computer program** which implements the conversion was developed during the project and can be downloaded (http://surfacetemperatures.blogspot.no/2014/06/understanding-effects-of-changes-in.html). It provides a quick and reliable conversion of temperature data from the ITS-27 through all the international temperature scales up to the current ITS-90. The program is implemented in visual basic. It is simple yet effective in design and can batch convert large amounts of temperature data from files. The look is shown on following figure (figure 26).

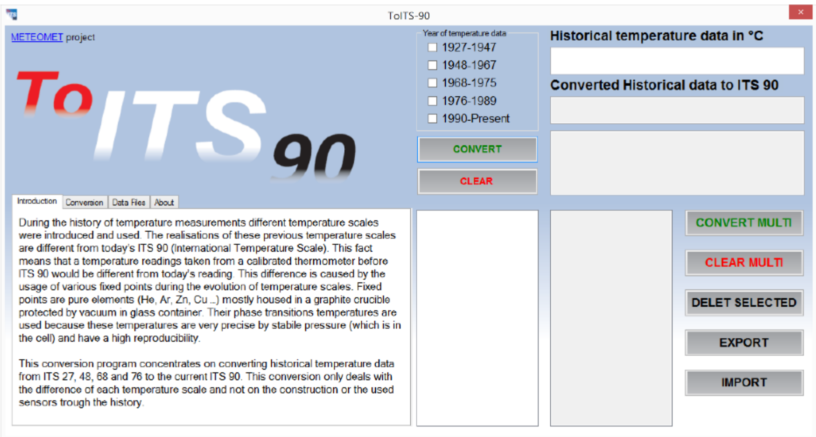

Figure 26. Look of the program**.**

The year selection of the data's origin is manual. The results of change according to the time is shown at following table.

Table 6: Difference in mK for typical temperatures.

	Difference in mK between historical data and ITS-90 for typical temperatures.					
Year	**at 25 °C**	**at 15 °C**	**at 5 °C**	**at -5 °C**	**at -15 °C**	**at -25 °C**
1927-1966	-13.5	-8.8	-3.0	4.0	11.8	19.8
1976-1989	-5.6	-3.2	-1.1	0.9	2.9	4.9

Original recorded temperature data series contain discontinuities in measured values. Detection of the breaking points can be done with several mathematical and statistical methods. Usually, any method does not include the contribution due to the instrument uncertainty into calculation. Final result of project is the proposal of a procedure, to allow the inclusion of instrumental uncertainty into processes of inhomogeneity detection.

Conclusion – Objective achieved:

a) An estimation of the instrumental contribution to temperature records in historical series was evalutated based on technical information about different kinds of thermometers used and its evolution during more than one century. Data was made available for possible inclusion in trend analysis by the climate community. A Grant associated with the project at the Spanish Climate Chance Center allowed the output of these results to interested researchers, together with results on the evaluation of the contribution to temperature measurement uncertainty due to instrument change.

b) Software was made available to automatically correct temperature records, including from large data files, with respect to the change due to the effect in the standards from different temperature scales of 1927, 1948 and 1968, to convert all values to IST-90 values for a more robust comparability. The software was delivered to the world scientific community of climatologists of the International Surface Temperature Initiative, collaborating with MeteoMet.

4 Actual and potential impact

4.1 Summary of dissemination activities

To promote the uptake of the new calibration techniques and facilities, project results were shared broadly with scientific, meteorology, climate change and industrial communities. 29 papers have been published in international scientific journals (listed in the next section), and input has been provided for 6 measurement guides, being completed under the follow-on EURAMET project ENV58:MeteoMet2. 26 separate training sessions have been delivered, and presentations were made at over 90 events, including the 2014 Metrology for Meteorology and Climate workshop in Slovenia. The workshop was attended by a wide range of meteorology researchers and practitioners, and allowed project results to be shared with a broad section of the meteorology community.

During the project 5 **guides** were produced:

1. Procedure for On-Site Calibration of Ultrasonic Anemometers (produced by TUBITAK)
2. Meteorological thermometers calibration in laboratory: procedure, problems and challenges (produced by INTIBS)
3. Procedure proposed for harmonising measurements with different solar radiation shields (produced by SP)
4. Tests and validation of data logging software for automatic weather stations (produced by UL).
5. Procedures for the combined laboratory calibration of temperature, humidity and pressure sensors in weather stations (produced by MIKES)

In addition, the information available also in other forms (papers, posters, presentations) was composed into a guiding document called: "A review of best practices in meteorological sensors calibration: lessons learned in ENV07 MeteoMet project". The full package of guiding documents will be made available at WMO level.

A total of 29 journal **papers** have been published or submitted to peer reviewed journals or conference proceedings, including to:

- International Journal of Thermophysics

- Review of Scientific Instruments
- Measurement Science and Technology.
- Climate of the Past
- Journal of Automation, Mobile Robotics & Intelligent Systems
- International Journal of Climatology
- Journal of Atmospheric and Oceanic Technology
- Meteorological Applications
- Metrologia
- Measure

A list is provided in section 6

A total of 26 **training events** were delivered by JRP participants. These included training delivered in person to trainees in Poland, Slovenia, Italy, Germany, Spain, Finland, Sweden and Nepal, as well as several training webinars.

Presentations at events far exceeded the target, reaching audiences at 95 events, such as:

- XIV National and V International Technical-Science Conference "Metrologia w Technikach Wytwarzania" 2011, Poland
- CIMO Training Workshop on Metrology for the English-speaking countries of Region V, November 21-25, 2011 (Australia)
- 4th GRUAN Implementation-Coordination Meeting (ICM-4) March 2012, (Japan)
- 9th International Temperature Symposium, March 2012, (USA)
- 2012 Measurement Science Conference (MSC), 2012, USA
- EURAMET TC-T EMRP Workshop 2012 Turkey
- 12th European Meteorological Society (EMS) Annual Meeting & 9th European Conference on Applied Climatology (ECAC), 2012, (Poland)
- Taking the temperature of the Earth" 1st annual EarthTemp Network meeting 2012 (UK)
- WMO TECO-2012 conference, 2012, Brussels,
- 5th GRUAN Implementation-Coordination Meeting (ICM-5) 2013, Netherlands
- Škola měření teploty a vlhkosti 2013
- METEOMET Midterm meeting, 2013 Italy
- EGU 2013
- Spanish National Congress, Spain, 2013
- 13th EMS Annual Meeting & 11th European Conference on Applications of Meteorology (ECAM) 2013, United Kingdom
- ICAM 2013, Kranjska gora, 2013, Slovenia,
- 16th International Conference on the Properties of Water and Steam, 2013, UK
- XVI Italian Congress of Agrometeorology AIAM 2013, Italy
- VI Congress of Metrology 2013, Poland
- Conference "Lasermethoden in der Strömungsmesstechnik" 2013, Germany
- Tempmeko 2013,Madeira, Portugal, 2013 (at least 13 presentations)
- INRiM technical seminar, Italy , 2013
- Institute of Meteorology and Water Management meeting, Poland, 2014
- Measurement problems in meteorology, INTiBS, Poland, 2014
- EGU2014, Vienna.
- Academy of Sciences, World Metrology Day, National celebration May 2014
- IMBiH Workshop with Bosnia Meteo Services 2 April 2014
- XVII Italian Congress of Agrometeorology AIAM 2014 - Italy
- NCSLI 2014, USA
- MMC2014 International workshop on Metrology for Meteorology and Climate, September 2014 Brdo, Slovenia
- Traceability for meteorological measurements - MeteoMet training17 September 2014, Brdo, Slovenia
- Plus presentations at private meetings during the project

Of special note among these was the **international workshop** Metrology for Meteorology and Climate, in Brdo, Slovenia, from September 15th to 18th, attended by about 100 participants. The event was conceived within the MeteoMet JRP in collaboration with stakeholders. The workshop attracted participation from a wide variety meteorology researchers and practitioners, making up almost half the attendees. The associated training event attracted more than 40 participants of which about half were users of the measurements. The event as a whole provided effective dissemination of results, and enhanced engagement with the meteo community. The dedicated web site remains open at http://www.mmc-2014.org. As well the full conference programme, all abstracts are available to download. Selected full papers have been submitted for publication in a dedicated special issue of Meteorology Applications (peer-reviewed SCI journal of UK Royal Meteorological Society), and Acta IMEKO open source web journal has undertaken to consider submissions of remaining full papers, extended abstracts and communications from the event.

Stakeholder Engagement

Since the project commenced, activities have consisted of setting up communication systems, engaging stakeholders and disseminating information. The project has had a great impact on a wide audience: 6 universities, 12 industries, 4 research centers, 15 meteorological organisations and 3 international reference networks have joined the project as collaborators and many other have expressed interest for results.

At international level, active liaisons were established with WMO, WMO Commission for Instruments and Methods of Observation (CIMO), WMO-GCOS Reference Upper Air Network (GRUAN), International Surface Temperatures Initiative (ISTI), and Slovenian Environment Agency (ARSO).

The collaboration with GRUAN has brought the project Coordinator to become a member of the WG Atmospheric Reference Observation of GRUAN. As first activity, the project Partners were involved in the revision of the GRUAN Manual and Guide. A strong recommendation was made to adopt the GUM (Guide to the Expression of Uncertainty in Measurement) as core guide for the evaluation of uncertainty and for the correct terminology. The new revision of the guide and manual in progress will take account of this suggestion. This work has represented a first attempt to bring a new level of metrology interaction to meteorological stakeholders.

Partners are in active liaison with ISTI as member/affiliate members of the ISTI steering committee and ISTI Working Group on Benchmarking and Assessment of homogenisation algorithms used to build climate datasets.

Project members are part of the COST action Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC).

In July 2013, the EURAMET General Assembly awarded the EURAMET Impact Prize to the ENV07 JRP-Coordinator, Dr Andrea Merlone. A relevant part of the impact achieved by JRP ENV07 MeteoMet was based on the personal proposal, organisation and involvement of the JRP-Coordinator in dissemination activities such as workshop in different nations also outside Europe, seminars at universities in different countries, visit to meteorological sites and constant exchange of technical information. The prize will be delivered to Andrea Merlone in October 2013 during TEMPMEKO Conference.

4.2 Intermediate impacts

Calibration services developed and now launched will provide long-term provision of measurement traceability with increased relevance to climate and weather applications. By developing relationships between NMIs and meteorology organisations, long-term cooperation is being established that can last well into the future.

This large consortium has offered a wide forum for discussing and proposing common procedures. NMIs operating at a regional level in cooperation with meteorological institutes have disseminated more efficiently and directly the results and best practices with the awareness that reliable climate data is a geographically equally relevant matter.

This project has engaged with the WMO, which sets defining procedures for observations of weather and climate worldwide. The project input promotes and supports the correct implementation of measurement traceability and measurement uncertainty wherever practicable.

The take-up of results by end users has been through: inputs to WMO guidance documents; training of meteorologists; development of calibration services intended for long-term availability; and by developing relationships at local level between NMIs and meteorology organisations, with the aim of sustaining long-term interactions well into the future.

Environment technical groups in frames of CIPM CCT and EURAMET TC-T have now been appointed, as a mechanism for extended future progress, putting climate and weather firmly on the agenda of these Metrology forums in an explicit way. In addition, nominees from the metrology community have been appointed by invitation to WMO Expert teams:

- INRIM to A1 Expert Team on Operational In Situ Technologies
- NPL to A.2 Expert Team on Developments in Situ Technologies
- CEM to A.3 Expert Team on Instrument Intercomparisons
- NPL to C.1 Expert Team on Operational Metrology.

This provides a framework for long-term collaboration to ensure lasting availability of metrology expertise to decision-making groups in WMO in support of best practice in meteorology and climate science.

All the top-level goals of this project will be carried forward in the follow-on EMPIR JRP MeteoMet2, where interactions will continue to be strengthened, and where improved and more robust metrology will be extended to a wider set of climate variables and problems.

Ultimately, by ensuring that climate measurements are traceable to their underlying SI unit definitions, measurement uncertainties in climate data will be reduced, and the accuracy of climate models can be improved. In the short-term, weather forecasts and weather warning systems can be made more exact, supporting a range of economic sectors including energy, transport, and agriculture. Over the longer-term, more accurate climate models are crucial to monitor and predicts the progress of climate change, and will help in the mitigation of its potentially severe social and economic effects.

5 Website address and contact details

A public website has been open, where the main public deliverables have been made available for the end-users and keep them informed about project meetings and events: www.meteomet.org.

A partners' restricted area has also been created, in order to give the possibility to all the partners to share work documents and deliverables.

The contact persons for questions about the project are:

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