TRACEABILITY OF GROUND-BASED METEOROLOGICAL SURFACE TEMPERATURE MEASUREMENTS

C. García Izquierdo[1], F. Bertiglia[2], R. Benyon[3], D. del Campo[1,] M. Dobre[4], V. Fernicola[2], D. Hudoklin[5], E. Grudniewicz[6], M. Heinonen[7], P. Klason[8], C. Holstein-Rathlou[9], J. Johansson[10], H. Kaykısızlı[11], G. Lopardo[2], C. Melvad[12], J. Merrison[9], K. Migała[13], A. Piccato[2], G. Roggero[2], P. Spazzini[2], A. Szmyrka-Grzebyk[14], S. Ruíz[1], A. Merlone[2]

[1] CEM, Centro Español de Metrología, Alfar, 2, ES-28760 Tres Cantos, Madrid, Spain

[2] INRiM Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 73, I-10135 - Turin, Italy

[3] INTA, Instituto Nacional de Técnica Aeroespacial, Ctra a Ajalvir, 28850, Torrejon de Ardoz, Spain

[4]SMU, Federale Overheidsdienst Economie, KMO, Middenstand en Energie - Dienst Wetenschappelijke Metrologie, Bd. Du Roi Albert II, 16, 1000 – Brussels, Belgium

[5]MIRS/UL-FE/LMK Univerza v Ljubjani, Trzaska 25, SI-1000 Ljubljana, Slovenia

[6]GUM Glówny Urzad Miar, Plac Trzech Krzyży 3/5 00-507 Warszawa, Poland

[7]MIKES Mittatekniikan Keskus, Tekniikantie 1, P.O. Box 9, FI-02151 Espoo, Finland

[8]SP, Technical Research Institute of Sweden, P.O. Box 857, SE-501 15 Borås, Sweden

[9] AU, Institut for Fysik og Astronomi, Aarhus Universitet, Ny Munkegade. byg. 1520, 8000 Aarhus C, Denmark

[10]Chalmers University of Technology, Onsala Space Observatory, SE-43992 Onsala, Sweden

[11]TUBITAK Ulusal Metroloji Enstitusu, Gebze Yerleskesi 54, TR-41470 Gebze, Kocaeli, Turkey

[12]DTI Teknologisk Institut, Gregersensvej, DK-2630, Taastrup, Denmark

[13]Uniwersytet Wrocławski, ul. Kosiby 6/8, 51-670 Wroclaw, Poland

[14]INTiBs, Institut Niskich Temperatur i Badan Strukturalnych IM. Wlodzimierza Trzebiatowskiego Polskiej Akadamii Nauk, Okolna str 2, 50-422 Wroclaw, Poland

E-mail (corresponding author): mcgarciaiz@cem.minetur.es

ABSTRACT

In the contest of the European MeteoMet project, a rigorous metrological approach is applied to measurements of atmospheric parameters such as temperature, pressure, humidity and airspeed in the atmosphere. This approach is addressed to both the study of new instruments and the definition of calibration procedures through the development of new dedicated devices.

This work describes how meteorological data can be made traceable to national standards with an associated Type B uncertainty budget to be added to the usual Type A. Type B uncertainty will be investigated as contributions from instrument capabilities and resolutions, calibration procedure adopted, inclusion of variance and covariance matrixes for the mutual influence of other quantities, such as pressure, humidity, solar irradiance and wind speed on the temperature values. A focus on the solar radiation protection shields quality and ageing is included, as direct influence on the temperature readings of weather stations. Two special chambers, here described, will be manufactured for the purpose, for laboratory and in-situ calibration of automatic weather stations.

The definition of protocols and calibration procedures for air temperature measurements (and in general for meteorological parameters), as proposed in the MeteoMet project, will open a new possible scenario: classes of data will be defined based on instruments calibration procedures, method and frequency, traceability chain, inclusion of mutual influence of measured parameters etc. The diffusion of such a new assessment will allow advantages in terms of quality of meteorological input data and more reliability of stored datasets for climate change studies. This

work is an example of application of metrological procedures to improve climate measurements in response to the CCT Recommendation and WMO expressed needs.

1. INTRODUCTION

In the frame of the European Metrology Research Program (EMRP), the MeteoMet project started its activities in November 2011. This project includes a work package dedicated to traceable measurement methods and protocols for ground based meteorological observations, in which 16 partners from different European countries are involved.

This work package aims to improve the reliability of weather stations measurements and to assure traceability to National Standards for measured parameter.

Today conventional calibrations of weather stations are performed by comparison, usually calibrating only one parameter at a time. The general lack of analysis of the mutual influences of the parameters leads to systematic errors in the calibration process. In addition, accurate methods for in-situ calibrations of weather stations, including those operating in extreme weather conditions, are currently absent.

Although standard operating procedures and data quality objectives are in place for some measurements [1], extensions to a wider range of applications and parameters (temperature, pressure, humidity, wind speed, solar radiance) and improvements of existing procedures and measurements are necessary [2]. 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. The definition of measurement standards remains a key issue for WMO, which has supported the collaboration between meteorology and measurement science communities in order to ensure the development of standards and the delivery of highly accurate data for atmospheric and climate monitoring in support of the implementation of the Global Framework for Climate Services, established by the World Climate Conference-3 (Geneva, 31 August - 4 September 2009). In April 2010, WMO became the second intergovernmental organization to sign the CIPM (International Committee of Weights and Measures) Mutual Recognition Arrangement (CIPM-MRA).

This paper presents the metrological approach to the study of the mutual influence of the different sources of uncertainties in the calibration of ground-based meteorological stations and reports the progress of the development of a dedicated facility for the combined and simultaneous calibration of temperature, humidity and pressure sensors in weather stations.

2. UNCERTAINTIES IN THE CALIBRATION OF GROUND-BASED WEATHER STATIONS

Assessing climate change will depend crucially on the uncertainties associated with measurements and the robustness of climate data. Measurement uncertainties can only be determined and hence minimised if proper consideration is given to the metrological traceability of the measurement results to stated standards.

An uncertainty budget should include the measurement model (mathematical relation among known quantities) to be involved in a measurement, estimates, and measurement uncertainties associated with the quantities in the measurement model, covariances, type of applied probability density functions, degrees of freedom, type of evaluation of measurement uncertainty, and any coverage factor. Measurement uncertainty comprises, in general, many components; all of them can be characterized by standard deviations and are divided in two groups. Type A, where the standard deviation is from a statistical analysis of series of measurements, and type B, where the evaluation of uncertainty is calculated by means other than statistical analysis, based on experience or other information. The fundamental reference document to perform the uncertainties calculation is the Guide to the Expression of Uncertainty in Measurement (GUM) [3].

The weather stations are complex instruments equipped with different sensors to measure temperature, humidity, barometric pressure, wind speed and precipitation amount. Standardised sensors are subjected to different performance tests to evaluate their behaviour under a range of conditions. For instance, EN 60751 [4] establishes a test for flowing air at a velocity of only 3 m/s, which means that the effect of air at higher velocities on temperature measurements is unknown.

Furthermore, there are no tests prescribed to evaluate the sensor behaviour in salinity environments, so their performance in beach-side locations is also unknown.

In consequence, to perform a reliable uncertainties calculation allowing the metrological traceability, it is necessary to study the mutual influence of the different sources of uncertainty (like wind speed and solar radiation in the measurement of temperature, pressure or humidity) and other ones not yet studied (like salinity). To do that, different tests, described in the following paragraphs, have been designed to perform the study.

2.1. Performance of temperature, humidity and pressure weather station sensors in extreme conditions

To carry out this work several sensors among the most common ones will be studied (thermistors and pt-100 for temperature and capacitive sensors for humidity and pressure). The study will consist in the characterisation of such sensors simulating different temperature, humidity and altitude conditions: -40 ºC to 50 ºC; 0 % Rh to 95 % Rh; 700 hPa to 1150 hPa. The number of calibration points in each range are defined and recorded according to the sensor resolution and procedure adopted; the behaviour of the different sensor with respect to fast changes of the environment conditions, in terms of response time, is investigated together with their stability.

2.2. Influence of the wind speed in the performance of the weather stations

Air flow velocity influences the temperature and humidity sensors through variations in heat transfer between the sensors and ambient air. Because of the dependence of static and dynamic pressure on the air velocity, also pressure sensors are affected by the wind speed. In weather stations, these phenomena change the readings and the measurement results for temperature, humidity and pressure, usually well over the instrument resolutions. Therefore, the wind speed influences should be modelled for each kind of instrument, due to the very different shapes, assembly structure, masses of the several existing weather stations. The influences can be taken into account by applying a correction function, with associated uncertainty, or as an uncertainty "tout court" if a model for the correction function is hard to be obtained or the amount of correction is small. To evaluate this source of uncertainty, under the MeteoMet project, tests are performed in three different wind tunnels, whose main characteristics are listed in tables 1 and 2. The tunnels described in table 1 belong to Spanish institution, INTA, Instituto Nacional de técnica aeroespacial and they will be used to assess the performance of temperature, humidity and pressure sensors subjected to controlled conditions of wind speed (1 m/s ≤ v ≤ 40 m/s) at ambient temperature. Mainly two aspects are examined: the influence of the positioning of the weather station in the wind tunnel and the behaviour of the different sensors with respect to fast changes of the wind condition.

Tunnel ID	**Open test section**	**Maximum speed**	**Reynolds number range**	**Turbulence level**
#1	(3.30 x 2.15 x 3.34) m^3	60 m/s	0 to 4 $x10^6$/m	0.5 %
#2	(2.8 x 1.9 x 4.9) m^3	60 m/s	0 to 4 $x10^6$/m	0.25 %

Table1. Features of the wind tunnels of INTA

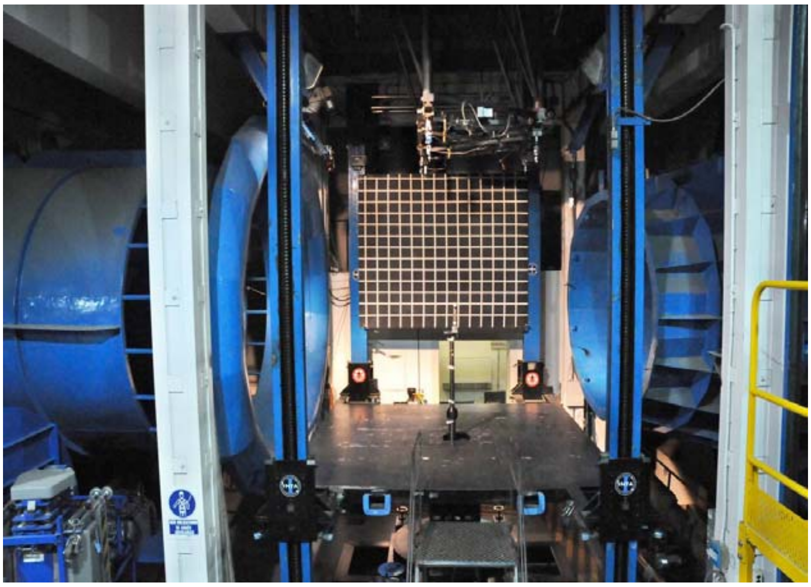

Figure 1. One of INTA wind tunnels

The Danish institute, AU, Institut for Fysik og Astronomi is the owner of the tunnel described in table 2, used to test equipment for Mars missions and called “Mars simulator”. In this JRP the facility will be adapted to Earth conditions and meteo sensors are going to be tested and characterized under by varying temperature, humidity, pressure and wind speed. The central aim is to use the AU tunnel as a laboratory test and calibration facility for meteorological instrumentation. This implies the modification of the current AU tunnel design to improve its specifications, mainly its temperature uniformity and to have a better control of the wind turbulence. After the modifications and before its use as a calibration chamber, it’s needed a new characterization of the wind tunnel to quantify the wind tunnel’s operating parameters.

Closed test diameter	Temperature	Humidity	Pressure	Air speed
(2 x 1 x 8) m^3	(-120, 50) ºC	Dewpoint controlled	(0.02, 1) bar	Low pressures: (1, 25) m/s 1 bar: (1, 10) m/s

Table2. Features of the wind tunnels of AU

Figure 2. AU wind tunnels

2.3. Influence of the salinity in the performance of temperature, humidity and pressure weather station sensors

Salinity it is not only a cause of malfunctioning of the weather station sensors but also a source of uncertainty never investigated so far. The sensors are ageing in a salinity chamber (see figure 3) and control calibrations are performed periodically to evaluate their stability and possible drifts. The humidity sensors are particularly monitored. These sensors will be especially cleaned and checked to understand the limits of the possible recovery and ageing correction and uncertainty.

Figure 3. CEM salinity chamber

2.4. Influence of the solar radiance in the performance of the weather stations

As it has been told, several factors influence the quality of the recorded weather data. One of the most severe however is thermal radiation: direct as well as indirect solar and infrared (IR) from the surroundings and the ground. This is due to the necessary protection shield for precipitation and direct sun radiation, firstly, is heated under solar radiation and secondly, hinders the free air movement. As a consequence, the environment causes systematic errors in the sensor readings. To drastically reduce this influence, mechanically aspirated radiation shields can be used, but are not in general use due to higher power consumption. Several reports have been published on this issue by WMO and other research Institutions. Then, at present, there is no commonly accepted reference screen design, nor are there, generally accepted test methods to determine the performance characteristics of screens.

The objective of the work is to evaluate the effect of solar radiation and ground thermal exchange on climate measurements. To do that, a standard radiation shield is being designed and constructed, in terms of materials, reflective paints and construction, investigating both active self ventilation and forced mechanical ventilation, where active self ventilation is a technique that, without external energy sources, increases ventilation when sun radiation is rising. A suitable thermal design, in order to improve the air temperature measurement accuracy and uncertainty will be defined. These new radiation shields will be tested under sun radiation or in sun simulator by comparison with traditional housings and after that, the reference housing will be compared with others used at present in two very different locations, in terms of weather conditions: Sweden and Spain. A long-term comparison (around 1 year) of the selection of different housings with the reference housing will be carried out. In both locations, the same kind of sensors will be used and it will have a continuous readings record of temperature, wind speed and radiation. This will allow, firstly, the study of the temperature error data as function of the radiation intensity, wind speed and the aging of the selected housing and the reference housing, secondly, the development of a temperature correction model as a function of the radiation intensity and wind speed and finally, to develop a proposal of procedures of harmonising measurements with different solar radiation shields.

Figure 4. Reference houses constructed by SP

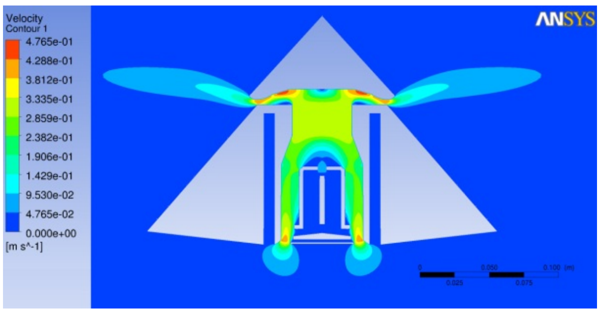

Figure 5. The reference housing modeled in Fluent

2.5 Traceability of wind speed measurements

Wind speed in the field is typically measured by cup, propeller or ultrasonic anemometers. But only ensuring traceable calibration of the anemometers would have little impact, if the strong dependence on the surrounding environment on the wind speed measurement would not also be addressed. The influence from the surrounding environment can be caused, firstly, by disturbing local geography and/or buildings and secondly the influence of rain and ice, mainly in ultrasonic anemometers.

To minimize the effects of the first point, a novel on-site calibration method of the wind speed instruments will be developed. The wind speed at a height of 40 m or 50 m is measured by a laser system and the obtained values are related with the wind speed at 10 m of height, where the automatic weather station is located. This relation will be established for different environments, different wind speeds and directions and although it isn't perfect, the anemometer measurements will be more reliable and will be traced to national standards.

To address the second point, a mathematical model will be tested and optimized to describe the effect of rain droplets, ice growth etc. on ultrasonic anemometers. To do that, measurements will be done in specially equipped wind tunnels with a laser Doppler anemometer as reference controlling e.g. seeding, ice growth or rain droplets. These measurements will allow an accurate estimate of the effects and help improving the mathematical model.

Finally, it will be studied the change of readings, between about 1 m/s and 40 m/s, of several anemometers with temperature ranging from 10 °C to 40 ºC, relative humidity up to 90% and different wind directions.

3. NEW FACILITIES FOR WEATHER STATION CALIBRATION

Calibrations of weather stations are usually performed in situ by comparison. Standard instruments are located close to the station being evaluated. This procedure has metrological weak points [5] and it is not possible to evaluate the calibration uncertainty.

The Istituto Nazionale di Ricerca Metrologica (INRiM) in the frame of the MeteoMet project is working at the construction of two new chambers specifically designed for the calibration of weather stations and meteorological sensors.

The first task is to develop a laboratory based facility for the combined, simultaneous, calibration of temperature, humidity and pressure sensors used in weather stations. This facility will enable the impact of interfering quantities on individual calibration curves of temperature, humidity and pressure sensors to be studied.

The evaluation of the correlation between the sensors response curves will be achievable in terms of covariance and mutual influence analysis between the various parameters (temperature, pressure, humidity, and solar irradiance and wind speed influence on the measurement of other parameters). The task will develop protocols and calibration procedures for the calibration of temperature, pressure and humidity sensors in weather stations and undertake the analysis of the relationship between laboratory calibration and in situ calibration.

The inner part of the chamber will be designed and manufactured for the specific purpose of hosting different types of weather stations and sensors for meteorological observations. Air temperature, pressure and humidity will be controlled separately and independently over all the range expected on the Earth's surface, including extreme conditions and areas. The goal will be to achieve simultaneous temperature control within 0.05 °C between -40 °C and 50 °C, and pressure control within 100 Pa between 75 kPa and 110 kPa. Humidity sensor calibration by comparison will be carried out in the range 5 %rh to 98 %rh, with air temperature ranging from 0 °C to 50 °C, with an accuracy between 0.3%rh to 0.7 %rh. The facility will enable the generation of wind speeds up to approximately 30 m/s in the test chamber and it will be designed to contain a solar radiation generator in order to evaluate the effects of wind speed and possibly solar radiation on the temperature, pressure and humidity sensors under study, characterisation or calibration.

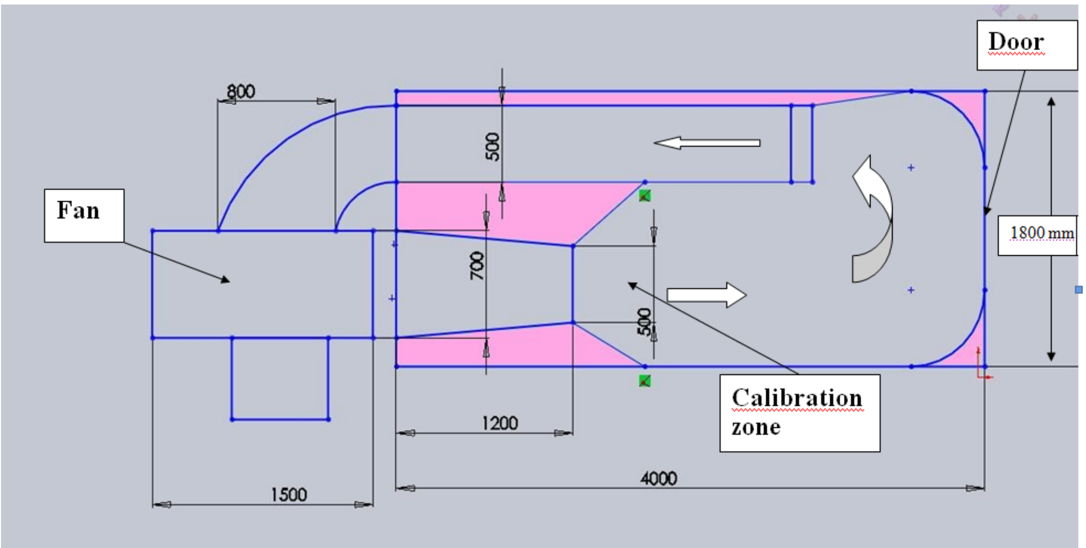

Figure 6: Laboratory facility for calibration of AWS with generation of wind.

A second facility studied at INRiM and made operative as one of the MeteoMet deliverables is a smaller dimensions transportable calibration chamber for the calibration of weather stations and sensors for meteorological measurements. This facility will enable simultaneous calibration of temperature, humidity and pressure sensors, covering the entire range expected based on the location of the station. It will feature temperature control within 0.05 °C between -20 °C and 50 °C, pressure control within 100 Pa between 50 kPa and 110 kPa, humidity calibration by comparison with 1.5 % uncertainty between 5 % Rh and 95 % Rh. The special chamber will be made with reduced dimensions such that it can be transported in a medium size vehicle. Initially, the device will be capable of temperature and pressure calibration meanwhile a dedicated humidity generator will then be developed. The three independently generated quantities (temperature, humidity and pressure) will be generated and measured using instruments directly calibrated against the primary standards. A first prototype of this chamber has been assembled in order to test the practical operations. In June 2012 a first campaign of calibration of meteorological sensors in situ has been made in cooperation with Società Meteorologica Italiana (SMI) using this first prototype of transportable calibration chamber made by INRiM and using sensors directly traceable to primary standards for temperature and pressure. The SMI sensors calibrated are those used to generate, and maintain, an historical temperature series lasting since the 19th century. A calibration curve was obtained and the instrument calibration uncertainty component evaluated. The final version, reported in figure 6 has been designed and manufactured. It has been ended in August 2012 and is under characterisation. A first definition of mobile humidity generator was delineated.

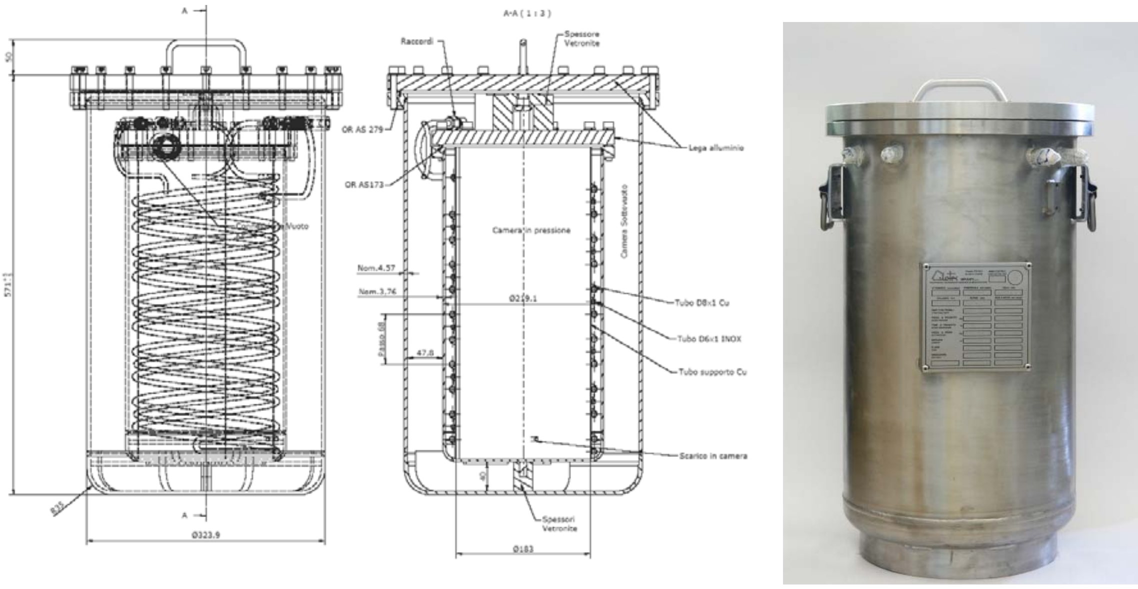

Figure 7: Chamber for in situ calibration chamber of AWS made at INRiM.

The reduced dimensions of the device will also make it adaptable for the calibration of weather stations and instruments used for the monitoring of high altitude environmental parameters. At present, weather stations on high altitude mountains are generally not calibrated. The innovative calibration chamber will be positioned by the REG Researcher (EV-CNR-K2) in the Pyramid Laboratory/Observatory at the base of Mount Everest in Nepal and will be used for the calibration of weather stations operating at research stations in the Karkonosze Mountains and at the arctic station on the Spitsbergen (Svalbard). The new facility is expected to bring benefits to the high altitude monitoring programmes fundamental for climate changes evaluation.

INRiM, in cooperation with Università degli Studi di Torino (UNITO), has also started the arrangement of a meteorological observation site in the close vicinity of INRiM buildings, in order to have a direct access with primary instruments, for the characterization of AWS (automatic weather stations) in situ calibration procedures, in cooperation with meteo staff operating in field. Further cooperation activities on the calibration of weather stations are being defined with the Italian Climate Consulting in order to check different procedures for the calibration of such instruments. The scope of this collaboration will be to evaluate the advantage of using specific equipment with respect to traditional climatic chamber. A blind comparison of the calibration results achieved by means of slightly different methods and different traceability “routes” will be performed.

4. CONCLUSIONS

This paper presents a metrological approach to the study of the mutual influence of the different meteorological magnitudes in the calibration of ground-based weather stations and reports the progress of the development of a dedicated facility for the combined and simultaneous calibration of temperature, humidity and pressure sensors in weather stations.

To guarantee the traceability of the weather stations, an adequate assessment of the uncertainties related to the performance of their sensors is necessary. In the MeteoMet project, the most common sensors are characterized in different environment conditions, even in extreme conditions, of temperature, humidity and altitude. The influence of wind speed, salinity and solar radiance in temperature, humidity and pressure measurements is also analyzed. The final objective is to estimate these sources of uncertainty and their mutual influence.

A standard radiation shield is being designed, constructed and characterized to study the influence of the solar radiation in climate measurements. A long-term comparison will be carried out between some select traditional housing and the standard shield to relate temperature measurements with solar radiation, wind speed and aging of the housing. This will allow from one side to develop a temperature correction model for solar radiation and wind speed and from the other side, to propose procedures for harmonising measurements with different solar radiation shields.

A novel on-site anemometers calibration method will be also developed, where the effect of disturbing local geography and/or buildings are minimizing. A mathematical model will be tested and optimized to describe the effect of rain droplets, ice growth etc. on ultrasonic anemometers

Two new chambers specifically designed for the calibration of weather stations and meteorological sensors are currently under construction. The first one enables to study the interaction between parameters such as temperature, pressure and humidity as well as to study the influence of the wind speed and solar radiation. The second one is a smaller dimensions transportable calibration chamber which will enable simultaneous in situ calibration of temperature, humidity and pressure sensors of weather stations..

The works described in this paper aim at responding the needs expressed by WMO and the request made by the CCT to implement metrological procedures in order to improve climate measurements.

5. ACKNOWLEDGEMENTS

These works are being developed within the frame of the EMRP, the EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

6. REFERENCES

[1] Guide to meteorological instruments and methods of observation (WMO-No.8) (2008).

[2] Blunden, J., Arndt D. S., and Baringer M. O., "State of the Climate in 2010". Bull. Amer. Meteor. Soc., 92 (6), S1-S266 (2011).

[3] Evaluation of measurement data – Guide to the expression of uncertainty in measurement JCGM 100:2008; http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf.

[4] EN 60751 Industrial platinum resistance thermometers and platinum temperature sensors.

[5] G. Lopardo, D. Marengo, A. Meda, A. Merlone, F. Moro, F. R. Pennecchi, M. Sardi, "Traceability and online publication of weather station measurements of temperature, pressure, and humidity" Int J Thermophys, (2012) DOI 10.1007/s10765-012-1175-3