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The Stancari air thermometer and the 1715–1737 record in Bologna, Italy

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Abstract This paper is focused on the closed-tube Stancari air thermometer that was developed at the beginning of the eighteenth century as an improvement of the Amontons thermometer, and used to record the temperature in Bologna, Italy, from 1715 to 1737. The problems met with this instrument, its calibration and the building technology in the eighteenth century are discussed in order to correct the record. The used methodological approach constitutes a useful example for other early series. The analysis of this record shows that the temperature in Bologna was not different from the 1961–1990 reference period. This result is in line with the contemporary record taken in Padua, Italy, confirming that this period of the Little Ice Age was not cold in the Mediterranean area.

1 Introduction

This paper deals with a unique 23-year record of a rather unknown air thermometer, early eighteenth century. The ancestor of the air thermometer, called *thermoscope* (Fig.1a), was invented at the end the sixteenth century and consisted of an air pocket whose volume changed with temperature or pressure changes. For this reason, quantitative measurements were impossible and the *thermoscope* was abandoned. One century later, Guillaume Amontons

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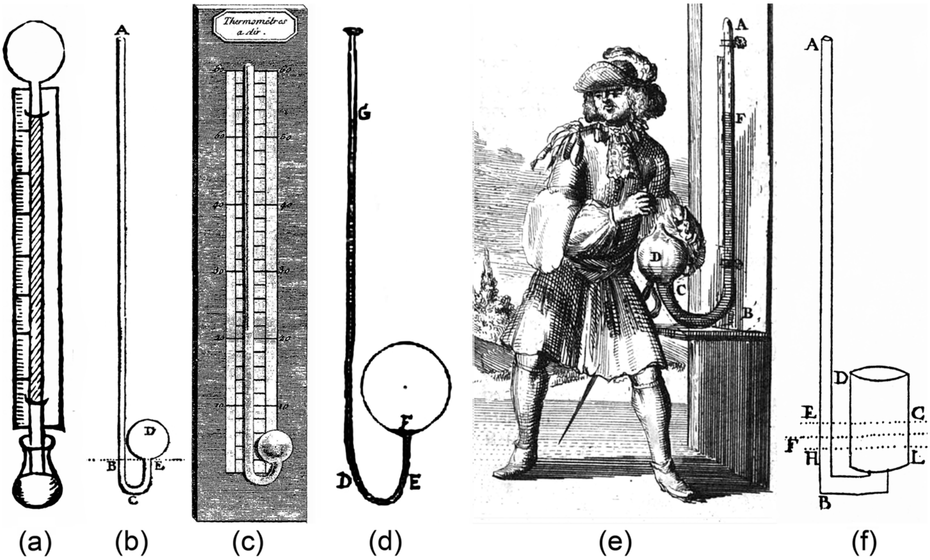

Fig. 1 Early air thermometers: **a** Sanctorius (1625); **b** Amontons (1702); **c** Amontons mounted on a tablet (Cotte, 1774); **d** Stancari (1708); **e** Stancari on a shelf (D** 1707); **f** Poleni (1709)

(1702) solved the problem of the open-tube air thermometer (Fig. 1b, c): it was sufficient to sum the readings of a parallel barometer (Online Resource 1). In addition, being a gas thermometer, he supposed that only one calibration point, i.e. boiling water, was sufficient to obtain an absolute thermometer. The contemporary use of a barometer was not a problem for an observer in a fixed place, but it was not practical in the case of field surveys.

In Bologna, the '*Accademia degli Inquieti*' (Restless-spirit Academy), later transformed into Institute and Academy of Sciences and Arts (IASA) (Zanotti 1739, 1745–1746; Bolletti 1751; Online Resource 2) was studying the problems encountered with the open-tube air thermometer recently invented by Amontons (1702). Geminiano Rondelli suggested that the Amontons thermometer would have been much improved if the influence of the atmospheric pressure were removed by sealing the top of the tube (Stancari 1708; Paul 1773; Pianciani 1833). Vittorio Francesco Stancari (Online Resource 3) with Francesco Vittuari built some thermometers of the improved type at IASA (Fig. 1d). In a letter to Giacomo Maria Maraldi, Paris Observatory, Stancari (1708) described the construction and calibration. This research was followed with interest because one year before this letter, Dalencé (D*** 1707) published (anonymously) a description of the instrument and a figure representing it (Fig. 1e). Unfortunately, Stancari died in 1709, aged 31.

The Stancari thermometer (ST) was appreciated by leading scientists (Beccari 1726; De Luc 1772; Spagnolo 1772; Paul 1773; Cotte 1774; Bellani 1816), but it had a short life due to some problems we will discuss later. One century later, Honoré de Flaugergues (1813) built some of these thermometers, claiming to be the inventor. His description closely followed Stancari (1708) and the plagiarism was soon recognized (Bellani 1816). The air thermometer had some drawbacks and was left abandoned until Joule and Thomson (1854), based on the theoretical studies of Carnot and Regnault, considered the constant-pressure and the constant-volume air thermometer and the absolute scale of temperature.

The sources report that a Stancari's colleague, Jacopo Bartolomeo Beccari, took regular readings with Gusmano Maria Galeazzi from 1715 to 1737 (Online Resource 3). This record is of exceptional relevance because is the only surviving record taken with Stancari thermometers and covers a poorly documented period in the middle of the Little Ice Age.

In the past, Baiada (1986) made an accurate research of documents and Comani (1987) analysed the series. However, the handwritten logs (Online Resource 4) are not easy to read and the thermometer was called "Amontons type, improved by Stancari" (Stancari 1708; Beccari 1724). Comani thought that it was a real Amontons and summed the barometer to the thermometer readings. The sum introduced a random noise and a seasonal bias of the same order of magnitude as the signal, and the result was a widely scattered set of misleading data (Online Resource 1). To reduce the scatter, she considered the yearly averages. The result was an obscure sum of yearly temperature and pressure averages. In addition, the summer months are affected by relevant gaps and this lowers the yearly average. For this reason it was necessary to start from the data recovery and clarify all obscure items, including this particular thermometer.

The methodological approach of this work combines a careful analysis of the historical sources and specific investigations on the readings to understand instrumental problems and apply appropriate corrections. The final aim is to produce and analyse a high-quality series of daily data over the early instrumental period.

2 The Stancari air thermometer

Stancari built his thermometer following the Amontons (1702) instructions, except for the top of the tube that was closed. The thermometer was composed of a glass tube, bent with a blowpipe flame into a J shape, and a hollow glass sphere (the bulb) (Fig. 1d). After the sphere was joined to the tube, the glass was carefully dried, the thermometer was kept tilted above the horizontal position, and some mercury was introduced from the top. Then, some air was forcedly blown into the bulb with a bellow. The almost horizontal position was necessary to operate with a small overpressure of mercury (Online Resource 1). Then the thermometer was kept standing; the bulb was plunged into a pot of water that was heated until boiling. The level reached by mercury was noted, and corrected for the atmospheric pressure, i.e. the departure of the barometric reading from 28 Paris inch (1 Paris inch =27.07 mm) that represent average pressure. This was the reference level, tuned by adding or removing some mercury. To seal the top of the tube, Stancari inclined the instrument to bring the mercury to the end of the tube and heated the glass above the boiling of mercury (i.e. 356.7 °C) until 700°-800 °C were reached and glass became plastic. At this point he thinned and hermetically sealed the top welding glass to the flame. This operation removed all air from the upper part. If an air bubble was visible reversing the tube, the operation was repeated (Stancari 1708; Galeazzi 1746).

Stancari built two thermometers 80 Paris inches long (2.16 m) and some others 8 or 9 inches less (Stancari 1708). Following Amontons (1702), the reference level was measured starting from the free surface of the mercury in the bulb and was divided in 73 parts that constituted the graduation of the scale. The distance between graduation lines varied from one thermometer to another, depending on the size of bulb and tube, the amount of air entrapped in the bulb, and the amount of mercury. The graduation of the scale was in Stancari degree (°S) divided in 8 or 12 lines. This scale was close to that indicated by Amontons (1702) in Amontons degree (°A), i.e. 1°A ≈ 1°S. The first thermometer used in Bologna had the column with 1°S equal to 12 lines of the Paris inch (herewith ST_{12}); the second 1°S equal to 8 lines (ST_8).

Beccari (1726) gave the calibration of ST_8 making reference to the Réaumur scale (°R), i.e. 51.2°S = 0 °R; 73°S = 80 °R, that means 1°S = 4.55 °C. Readings were expressed in °S, lines and quarters and the resolution was 0.14 °C. ST_{12} too had the same calibration in boiling water, but because the amounts of air and mercury were not the same, the response was different, in particular not linear, and ranged from 5.3 °C to 7.7 °C. The resolution ranged from 0.11 °C to 0.16 °C.

3 Observers

From the sources we know that Beccari observed in 1715 (Beccari 1715) and took readings with other thermometers from 1723 to the last day of his life in 1766 (Scarselli 1766). In 1726 Beccari wrote that the ST readings in his logs were taken by Galeazzi (Beccari 1726). It would be logical suppose that Galeazzi continued till January 7th, 1738. We know that Galeazzi left IASA in 1739 for having been appointed to the chair of Anatomy and this might have caused the end of the record. However, as we will see later, in 1727 the thermometer changed room and probably observer too.

Missing readings (Online Resource 5) from 1727 to 1737 account for 6.0 % of the total number of planned observations. Missing readings are not equally distributed among the three sampling times: 50.2 % of them are at 08:00; 32.8 % at 14:00; and 17.0 % at 22:00. Nocturnal readings were the most regular ones (i.e. 17.0 % of the gaps) while morning gaps increased in frequency (i.e. 50.2 %). If we consider the cloud cover of the nights before a morning gap, 17 % of the gaps occurred after non-precipitation days and 83 % in precipitation days. These figures suggest that the observer was an astronomer. The Director of Astronomic Specula was Eustachio Manfredi, a good friend of Stancari, Beccari and Galeazzi. Manfredi was often off for his public duties and very likely he charged his assistants for reading in this period. Eustachio Zanotti was his first assistant and became Director when Manfredi died. However, readings were stopped one year before he became Director, probably because he had to solve an increasing number of duties while Manfredi health was worsening.

4 The record: reading times and daily averages

From the antiquity till the beginning of the enlightenment period, the idea of mean was linked with the intermediate level between extremes, i.e. the so-called "*golden mean*" inspired to Aristotle. Climate was defined in terms of the so-called "*temperate*" that was the *golden mean* between the summer hot and the winter cold, For this reason the secondary stations of the Medici Network (1654–1670) operated only in the extreme seasons (Camuffo and Bertolin, 2012a), and a number of series in the eighteenth century had two readings, i.e. one at sunrise (supposed to be representative of the daily minimum) and another one or two hours after noon (supposed to be representative of the daily maximum), in order to get the daily golden mean. This golden mean closely approaches the modern 24 h average (Camuffo 2002b). In the case of consistent gaps in the summer season (Online Resource 5) the golden mean is less affected than the usual average over the available set of calendar days.

Beccari and Galeazzi departed from the above scheme and took three readings a day, i.e. at 8:00, 14:00 and 22:00, a choice that later inspired the *Societas Meteorologica Palatina*, Mannheim. The readings at 8:00 are the less relevant because they are poorly representative of the daily minimum because the time lag after sunrise was changeable with the calendar day. The readings at 14:00 are representative of the daily maximum. At that time, the observers tried to counteract the inertia of the building envelope with a good ventilation of the room for about half an hour. We know this practice from the contemporary Giovanni Poleni in Padua (Camuffo 2002a), but we have no precise indication from the Bologna observers. The readings at 22:00 are the most interesting ones because they closely approach the daily mean. This has been recognized from modern record (2004–2016) of Bologna where the difference between the temperature at 22:00 and the 24 h mean has been calculated (Fig. 2). The differences have been interpolated with a best-fit 6-order polynomial with standard deviation SD = 0.4 °C. The readings at 22:00 underestimate the 24 h average by −0.15 ± 0.4 °C in winter and overestimate it by 0.2 ± 0.4 °C in summer. For this reason we have corrected each reading at 22:00 for the above departure over the calendar day to make it representative of the daily average, as reported in Fig. 3.

The record is affected by discontinuities, i.e. from January 1st, 1720 the temperature was lowered by 3.6 °C and was followed by a drift (Fig. 4) that will be explained (and corrected) later.

5 Location, internal changes, room ventilation, and temperature drop

The instrument location was not mentioned in the sources. It may be logical to suppose that the thermometers were always kept in the same building, e.g. the observers' home or where they worked (Online Resource 2). A number of STs were built in Poggi Palace (Stancari 1708) and for practical reasons we believe that they have always been kept in that building, although moved from one room to another. The indoor/outdoor exposure was not specified because it was considered obvious: thermometers were not weatherproof and indoor measurements were considered normal, as James Jurin (1723) recommended some years later on behalf of the Royal Society, London.

The data analysis may clarify what was missed in the sources. From the readings in the logs it is evident that ST_{12} was used from January 1st, 1715 to January 26th, 1716 and from January 1st, 1727 to January 7th, 1738; ST_8 from February 5th, 1716 to December 31st, 1726, because readings were expressed in twelfths or eights, respectively. The reason for the thermometer substitution was not specified, but is related to two discontinuities in the record.

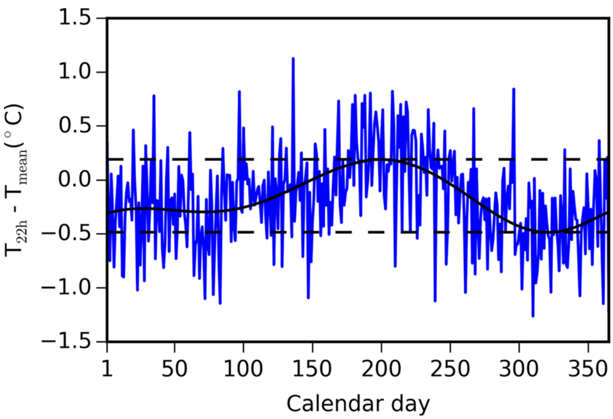

Fig. 2 Departure of the readings taken at 22:00 from the daily average temperature in Bologna, from 2004 to 2016. Solid line: 6-order polynomial interpolation; dotted lines: range of the interpolation line

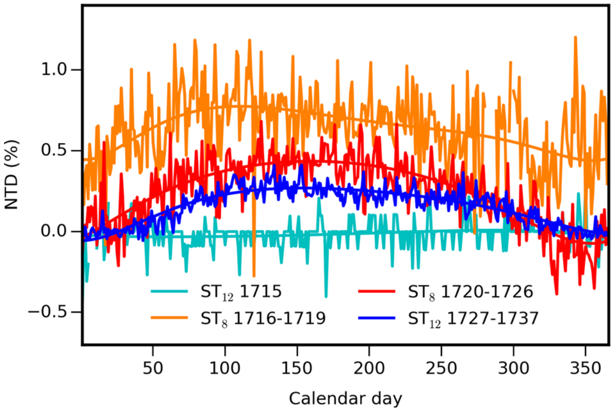

Fig. 3 Normalised temperature difference (NTD), i.e. the difference between the indoor temperature readings taken by Beccari and Galeazzi at 14:00 and 22:00 divided by the corresponding values in the modern reference period (1961–1990). Key: ST_{12} in 1715 (*cyan*); ST_8 from 1716 to 1719 (*orange*); ST_8 from 1720 to 1726 (*red*), ST_{12} from 1727 to 1737 (*blue*). NTD is representative of the room ventilation. In 1715 ventilation was absent; from 1716 to 1719 very good; from 1720 to 1726 good; from 1727 to 1737 poor

A useful parameter to recognize if readings were taken inside, outside, or in a room with a limited ventilation, is the daily span between readings or, if only one reading is available, the day-by-day variability (Cocheo and Camuffo 2002). In the case of unheated buildings, the difference between the temperature readings at 14:00 and 22:00 can be considered a room fingerprint parameter, strictly linked to the room ventilation, solar exposure and use. Its value is approximately half of the daily span. In this paper we have used the normalized temperature difference (NTD), i.e. the ratio between the observed diurnal temperature range (or a given portion of it) and the same but measured outdoors in the 1961–1990 reference period (Fig. 3). The normal range of NTD is 0 to 1, but it may exceed 1 in the case the direct solar radiation overheats the site. (For a quantitative evaluation of the solar energy impinging on the walls of the IASA rooms see Online Resource 2). The bias for different instrument inertia is negligible, because they were built in the same way and with the same materials; their departures are only related to slightly different air pockets. The result is summarized in Table 1.

In 1715, NTD was completely damped by the building envelope. This means that the thermometer was kept in an internal, poorly ventilated room, e.g. an underground room, or Room B without windows (for room details see Online Resource 2).

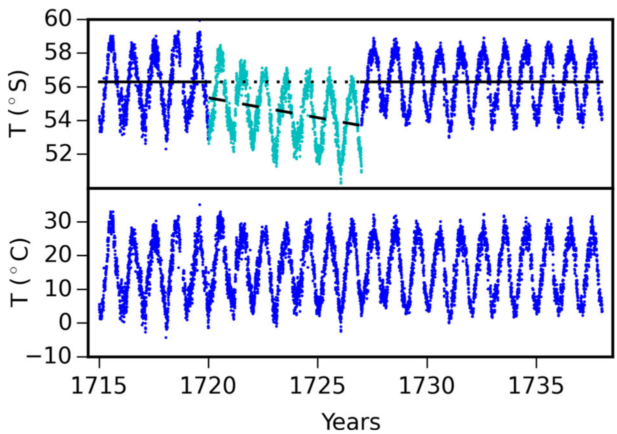

Fig. 4 Indoor temperature readings in Bologna, taken at 22:00 from 1715 to 1737. *Top*: original readings in °S. The cyan readings are affected by drop and drift of ST_8, in the period from 1720 to 1726. Solid line: mean value of unaffected data, i.e. excluding 1720 to 1726. Dashed line: linear interpolation of the affected data. *Bottom*: the above series but corrected for drop, drift and linearity, and transformed in °C

Table 1 Thermometer (Therm) locations at IASA and normalized temperature difference (NTD) for the 180th calendar day, when the daily span is maximum. The most probable Room is indicated

Period	Therm	NTD_{180}	Ventilation	Room	Notes
1715	ST_{12}	0	none	underground? B?	underground or internal room without windows
1716–1719	ST_8	0.74	very good	C, D, E?	changed thermometer and moved to a well-ventilated room
1720–1726	ST_8	0.45	good	F?	ST_8 moved and followed by drop & drift
1727–1737	ST_{12}	0.28	poor	Tower?	changed room and thermometer

On January 1st, 1716 the thermometer was moved to a well-ventilated room, i.e. one of the Rooms C,D,E,F, each with window. Rooms C,D,E were on the SE side and warmer; Room F on the façade, exposed to NNW with less solar radiation (Online Resource 2). We should exclude the Room F that will appear in the next step.

The drop observed on January 1st, 1720 can be explained with the thermometer moved from one of the Rooms C,D,E to Room F. As the room was cooler, the ventilation protocol before each reading was probably shortened, which may explain the smaller ventilation. Bolletti (1751) described IASA confirming that at his time thermometers and barometers were kept in the last room of the Physics Department, i.e. Room F. Although nothing was specified, in 1726 Beccari and Galeazzi recognized that ST_8 had cumulated a departure by 12 °C from the other thermometers that Beccari was using in parallel. They realized that the instrument was out of order and decided to dismiss it and return to ST_{12}.

In 1727–1737, NTD was further reduced, showing that the thermometer was moved to a poorly ventilated room. However, the average temperature was the same as in 1716–1719, suggesting the same exposure, but excluding the highly ventilated Rooms C,D,E. From 1714 to 1726, IASA built a Tower with rooms to keep optical and astronomic instruments; then the astronomer lodgement and the Astronomical Specula on the top (Bolletti, 1751). It is likely that Beccari and Galeazzi decided to move the thermometer to a room of the Astronomical Tower terminated in 1726 to benefit of the support of astronomers (i.e. Zanotti) for readings. In practice, both the room and the observer were changed.

In conclusion, NTD helps to recognize the rooms; the move from one room to another may explain the observed drop in 1720 and changes in ventilation, but not the 1720–1726 drift that requires further hypotheses to be investigated, as follows.

6 Drift

The seven-year drift that followed the drop occurred on January 1st, 1720, when ST_8 was moved and continued until December 31st 1726, when ST_8 was substituted with ST_{12}. The drift hypotheses need some discussion.

6.1 Tree shade

The shade of a growing tree may prevent light from reaching the building wall with cooling increasing over time. However, the cooling is expected to be different at the three sampling times, with low influence on nocturnal readings and daily minima. It should also show a seasonal cycle related to the solar orbit and the foliage. Finally, the presence of trees on the street in front of Poggi Palace is not confirmed in the illustrations of that time.

6.2 Scale or glasswork slippage

In theory, two types of slippage are possible. The former is the slippage of the graduate scale. One should consider that the glass tube with a column of some 1500 mm of mercury was very heavy, and the wooden tablet with the scale was gently fixed to the tube with an iron wire, hung to a wall (Camuffo and Bertolin 2012b). The iron wire cannot be fastened too much because the glass may break when the wooden tablet swells with dampness. If the wooden tablet had the scale drawn on it, a slippage at a constant rate might explain a drift. However, a downward slippage of the tablet would have caused an increasing temperature drift, i.e. the opposite, so this hypothesis should be rejected.

The slippage of the glasswork should consider the tablet hung on a wall and the heavy glass tube accidentally hit. This could explain both the drop and the downward slippage perceived as a decreasing trend, as observed. In this hypothesis, the tube had started slipping and continued at constant rate for seven years totalling about a 6 cm displacement, unnoticed to the observer. This is quite unlikely; in addition, it would have been sufficient to pull back the glass to the original position without substituting the instrument.

The drawing by D'Alencé (D*** 1707, Fig. 1e) shows that a shelf was used to support the heavy glasswork, while the graduated scale was on the vertical table fixed to the shelf. This suggests that any slippage was hardly probable; the instrument change in 1727 suggests another reason, i.e. that ST_8 was irreversibly damaged.

6.3 Weakness in sealing technology and thermometer vulnerability

The interpretation of the possible ways for air leakage requires a preliminary analysis of the most vulnerable parts of this thermometer, deriving from its building technology, i.e. how the top of the tube was hermetically sealed and how the bulb was fixed to the tube.

Stancari (1708) specified that he sealed the top of the tube at the blowpipe flame; the top became vulnerable because the glass was thinned and in addition some mercury might have remained entrapped inside the welding area. He did not specify how the bulb was fixed to the tube. Bellani (1816) wrote that Stancari sealed it to the blowpipe flame. To do it, both the sphere and the tube should be previously heated to 500°-600 °C in a furnace and then carefully sealed together with the flame. In addition, the sphere and the tube should have exactly the same composition and thermal expansion. If the glass welding was perfect, the junction could resist to moderately high temperatures and pressures. If the welding was not perfect, or made with the glasswork at an uneven temperature, the glass may hold residual internal stresses and eventually flaw or even break, always constituting a vulnerable part.

Another method to seal the sphere to the tube was "*mastic*", "*fire putty*" or "*glazing putty*" (Online Resource 6). When applied hot, they are soft, but strong binders after they become cold. They may last for decades, but in the long-term when they dry out, they shrink and crack and might explain leakage. However, all of the above binders are temperature sensitive and are softened or even melt when the bulb is plunged into boiling water for calibration. The high pressure (around 2 atm) exerted by the air pocket inside the bulb will violently separate the tube from bulb, making impossible the calibration. We should exclude this use for STs.

6.3.1 Glass cracking

One may suppose that glass was accidentally hit and cracked, allowing leakage. However, the drift should have an exponential trend, differently from the observed initial air exchange at very fast rate (i.e. the drop), followed by a slow, constant leakage for seven years (i.e. the drift).

6.3.2 Failure of the junction between tube and sphere

In this hypothesis, the tube and sphere were joined using a blowpipe flame (or some kind of putty). In case of micro-cracks, the difference in pressure across the junction was one atmosphere and may explain an outward leakage. The air pocket was in the upper part of the sphere and the junction was only in contact with mercury because the air reached the bottom at boiling water (Stancari 1708; Galeazzi 1746). The high surface tension of mercury impedes percolation through micro-cracks. We should assume cracks of a consistent size to allow mercury dropping. However, it is unlikely that mercury dropping on the floor passed unobserved for seven years.

6.3.3 Failure of the top welding

On January 1st, 1720 Galeazzi moved his thermometer to Room F. During the move, the mercury had free oscillations: when mercury was directed towards the bulb, the elastic spring of the air pocket damped the motion; when it moved on the opposite direction, it had no damping forces and crashed violently into the vulnerable top of the tube, flawing it. Inside the tube the pressure was 2×10^{-3} mmHg (0.2 mPa), i.e. the saturation pressure of mercury, and the external pressure was around 760 mmHg. The pressure difference across the micro-crack was around one atmosphere, and this is the only realistic hypothesis that can justify that some air was sucked in at a slow rate, causing the observed drift.

Briefly, the instrument move explains the drop and the failure on the top of the tube, i.e. the drift. Drop and drift have been corrected in this paper with linear interpolation to remove the bias, as shown in Fig. 4.

7 Deviation from linearity

In order to assess the precise scales of ST_8 and ST_{12}, it was necessary to plot these readings versus the readings of the Little Florentine Thermometer (LFT; Camuffo and Bertolin 2012a) taken by Beccari, used as a reference, over the common periods. The plot of ST_8 was linear and the plot of ST_{12} slightly departed from linearity (Online Resource 8). Three hypotheses can be made to explain the above deviation and needed a critical analysis to accept or correct data.

7.1 Moisture condensation inside the bulb

Stancari discovered that the moisture present in the air might change phase hazing the bulb glass and affecting readings (Zeno and Zeno 1714; Galeazzi 1746). When the air was blown into the bulb, the pressure was one atmosphere; when the thermometer was rotated upright, the mercury column increased the pressure very much (almost twice) and the volume of the air pocket was compressed. A change of phase may begin at a temperature threshold (TT) when the air pocket in the bulb reaches critical conditions determined by the initial conditions. The best air thermometers were built in winter, when the moisture content in the air is low.

Plotting the readings of ST_{12} versus LFT, TT may be obtained as the intersection of the two best-fit lines of the lower and higher temperatures (Online Resources 8, Fig. 8.3). One obtains TT = 56.45 °S (i.e. 15.4 °C). At TT, the bulb pressure corresponded to 1528 mmHg, almost twice (i.e. 2.01 times) the standard atmospheric pressure. To explain the problem, let us suppose that when ST_{12} was built, the ambient air blown into the bulb had a temperature of 18.7 °C and 50 % relative humidity (RH). When the thermometer was placed in the upright position, the pressure halved the volume of the air pocket, and the vapour reached saturation. One should expect that at T > TT, the vapour in the pocket behaved as a gas, and at T < TT the internal condensation reduced the number of moles and, consequently, the resolution of the thermometer. However, the plot is not compatible with this hypothesis because at T < TT we observe a higher resolution (i.e. 1°S = 5.3 °C) and at T > TT a lower one (i.e. 1°S = 7.7 °C) while we should expect the opposite. In addition, the number of moles of water vapour that should change phase to reach the same effect is not realistic.

7.2 Air on the top of the tube

In early thermometers with the tube hermetically closed on top, the free volume inside the tube above the column was filled with the saturated vapour of the thermometric liquid. Sometimes some air was deliberately left inside. At high temperatures, the free volume decreases and the pressure inside the top increases, partially counteracting the pressure of the air pocket in the bulb. However, a calculation (Online Resources 7) shows that, in the specific case of the ST used in Bologna, the temperature was generally $T < 30$ °C; less than 1/3 of the free volume was engaged, which excludes a relevant bias.

7.3 Spherical bulb

Amontons (1702) used spherical bulbs and the air pocket was a spherical cap with movable base, i.e. the free surface of the mercury. It reached the bottom at 100 °C.

From the record and the comparison with the LFT we see that the response of ST_8 was linear. This means that the air pocket was small and filled the upper half of the sphere. The free mercury surface moved up and down across the centre of the sphere without changing its surface area too much. The ideal solution was the Amontons thermometer used by Giovanni Poleni (1709) in Padua, who utilized a cylindrical bulb (Fig. 1f; Camuffo and Jones, 2002). When the bulb section is constant, the mercury moved to or from the tube changing the column height proportionally to the temperature change and the ratio of the sections of the cylinder and the tube (Camuffo 2002a). It should be noted that Poleni built his thermometer with the contribution of Gian Battista Morgagni, who was the head of the team where Stancari worked at the Restless-spirit Academy, and may have suggested this further improvement.

As opposed, with a spherical bulb, when the air pocket progresses towards the lower part of the sphere, the mercury column apparently rises at an accelerated rate. This was the case of ST_{12}. D'Alencé (D*** 1707) reported that in this thermometer the air pocket should fill ¾ of the spherical bulb and showed it in a figure (Fig. 1e and Online Resource 1). At high temperatures the air pocket expands into the lower part of the spherical bulb, and while the free surface of mercury becomes lower, its area becomes smaller and smaller following the curvature of the sphere. This requires an increasing displacement Δh_S of the surface to move into the tube the same volume of mercury, as explained in Online Resource 8.

In the ST, when the base of the air pocket fluctuates around the centre of the sphere, the thermometer response is to a first approximation linear, but when the air pocket progresses towards the lower part of the sphere, the mercury column apparently rises at an accelerated rate. The best-fit second-order equation that interpolates the plot of ST_{12} versus LFT (Online Resource 8 Fig. 8.3) is characterized by the determination coefficient $R^2 = 0.99$. This high value indicates that the hypothesis of a continuous acceleration at increasing temperatures is the best supported by regression tests.

7.4 Correction for non-linearity

The non-linearity of ST_{12} was corrected in this paper with a second-order equation obtained after comparison with the parallel readings made with LFT (°G), i.e.:

$$ST_{12}({}^{\circ}S) = ax^2 + bx + c$$

as illustrated in Online Resources 8.

8 Anomaly

All indoor readings were transformed to °C (Fig. 4) and have been made available with a daily resolution. The record has been compared with the 1961–1990 international reference period (Fig. 5). The average shows that in this part of the eighteenth century the temperature was 2.6 °C degrees higher than in 1961–1990. This difference is partly explained because the readings were taken indoors. The moving average shows a series of swings of 3–4 years. From 1715 to 1720 hotter summers and colder winters were observed.

The seasons in this period are shown in Fig. 6. Winter ranged from 3.4° to 7.9 °C, spring from 11.7° to 17.4 °C, summer from 23.9° to 29.2 °C, and autumn from 14.7° to 18.3 °C. No trends are visible, except for higher levels and a wilder dispersion of summer temperatures from 1715 to 1720.

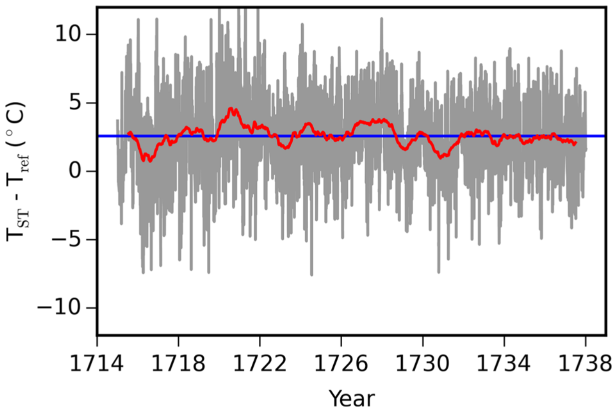

Fig. 5 Temperature anomaly (*grey line*), i.e. difference between the ST readings from 1715 to 1737 and the 1961–1970 reference period. *Red line*: moving average calculated with a 365-day window. *Blue line*: mean anomaly level

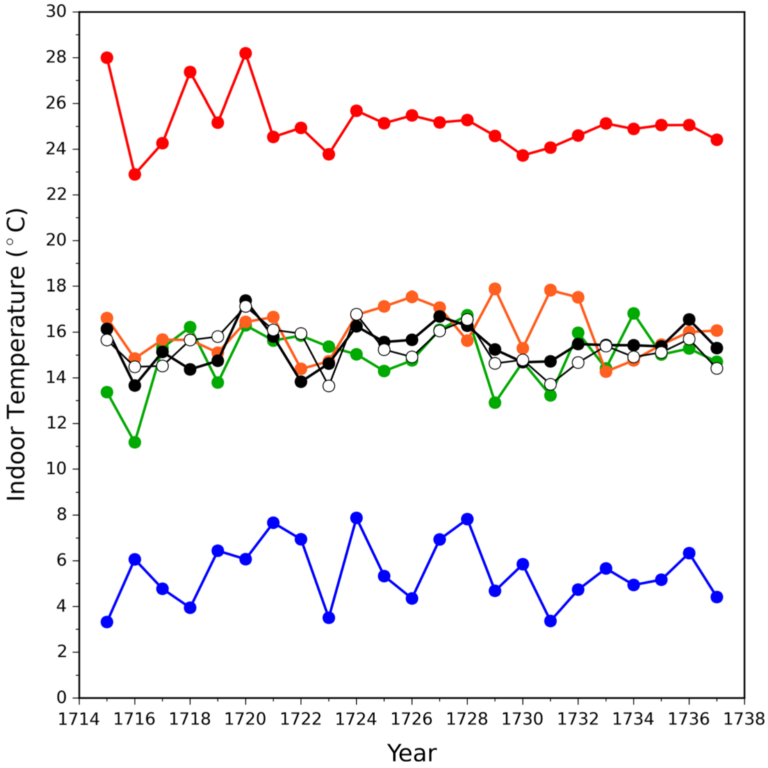

Fig. 6 Mean seasonal temperatures. *Blue*: winter; *green*: spring; *red*: summer; *orange*: autumn. *Black*: yearly mean temperature calculated over the whole set of calendar days; *white*: golden mean obtained from summer and winter

Estimated uncertainty bands are: ±0.15 °C readings; ±0.2 °C linearity and drift; ±0.3 °C approximation of the daily average. Following Taylor (1982), the overall uncertainty, derived from the sum of the squares of the above independent contributions, is ±0.4 °C. This is excellent quality for an early series.

An effort was made to see whether it was possible to apply a transformation to pass from indoor to outdoor values. Although the building is known, it was impossible an accurate evaluation of the indoor/outdoor relationship (Camuffo et al., 2014). The problem is that readings were taken three centuries ago in an unheated room, while the building now is seat of the University and Museum, with indoor climate regulated according to modern use. However, Beccari took other parallel series, with four thermometers kept in his house, in the same room, starting from 1723 and one external from 1742. From these records it has been possible to find the indoor-outdoor relationship for Beccari house, to calculate the outdoor temperature for the period before 1742 and find the indoor-outdoor relationship for Poggi Palace (Online Resources 9). The average indoor - outdoor difference for Poggi Palace is 2.4 °C, very close to the value found for the Beccari house. This is not surprising because the above difference is not representative of the usual indoor building climate (i.e. the building envelope), but of the room prepared for indoor observations with abundant ventilation operated before each reading (Cocheo and Camuffo 2002). Beccari and his Pupils (i.e. Galeazzi and Zanotti) strictly followed the same ventilation protocol and obtained similar results.

9 Conclusions

The indoor readings taken by Beccari, Gaelazzi, and Zanotti from 1715 to 1737 constitute the only known series made with Stancari air thermometers. Although the work to solve all uncertainties required several years, a rare instrumental series of the mid Little Ice Age has been produced.

This instrument was famous for one century; later it was neglected. The fortunate combination of having found this thermometer working in parallel with others (not presented here) has made it possible to become familiar with it. The Stancari air thermometer was difficult to build and calibrate. In particular, the use of putty to join the bulb to the tube was not compatible with plunging it in boiling water for calibration. Each instrument had a peculiar response and the scale in °S changed from one thermometer to another. It was long (2 m) and had high resolution, about 0.15 °C. It was vulnerable when moved from one place to another because the free oscillations of mercury could break the glass. When the air pocket reached the lower part of the spherical bulb, readings deviated from linearity. The problem would have been avoided using a cylindrical bulb, as Poleni did in Padua. No condensation inside the bulb was observed.

The instruments were always kept in Poggi Palace where they were built, although the thermometers had been moved from one room to another, as evidenced by the difference between readings at different times. The choice of sampling at 22:00 has been very fortunate for us, because it is closely representative of the daily mean.

The series is based on indoor readings and the average anomaly is +2.6 °C. Applying the indoor-outdoor difference found for Poggi Palace, i.e. -2.4 °C, the average outdoor temperature anomaly becomes +0.2 °C, in line with the results found with the contemporary series in Padua (Camuffo and Jones, 2002; Camuffo and Bertolin 2012b) and confirms that the 1715–1737 temperature in Bologna was not much different from the 1961–1990 reference period.

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Article Title: The Stancari Air Thermometer and the 1715-1737 record in Bologna, Italy

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Online Resource 1

The development of the air thermometer

The Thermoscope

The *Thermoscope* was presented by Galileo Galilei in 1593 to his students at the University of Padua to explain the expansion of gases (Sagredo, 1612). Some twenty years later, in 1612, it was applied to medicine by Sanctorius Sanctorius (Sanctorius 1625), at the same University. The instrument was composed of a graduated glass tube with a glass sphere acting as a bulb on the top (Fig.1.1a).

The sphere and the upper part of the tube contained an air pocket, while the bottom was immersed in a vessel, containing a liquid. Sartorius graduated the tube to read the height h_{TL} of the liquid column, but the response of the instrument changed with the size of the air pocket, the tube, and/or the sphere. This thermometer was initially used to pinpoint temperature changes on short time scales, because these raised or lowered the liquid column in the tube, but barometric pressure changes had the same effect. For the above difficulties, the air thermometer was abandoned. The instrument fell in complete oblivion in 1642, when Evangelista Torricelli and the Grand Duke of Tuscany invented the liquid-in-glass thermometer. This was a reliable instrument, the most popularly used in meteorology for the next 250 years. However, at the end of the 18th century, the studies of gases made by Robert Boyle (1662) and Edme Mariotte (1676), raised the attention to the air thermometer, once again.

The Amontons's air thermometer

From the new theories of gases by Boyle and Mariotte, Amontons (1702) recognized that the "spring", i.e. the elastic force of the air increased with the pressure and had the idea that the volume of an air pocket may reduce to zero at a sufficiently low temperature, while it expands at a known rate in the range of weather observations. He thought that a thermometer made with compressed air was very sensitive and needed only one calibration point; the most convenient being boiling water because it may be reproduced everywhere. Mercury was used to compress air. To this aim he considered it convenient to turn upside-down the Sartorius thermoscope to keep compressed air in the bottom and plunge the bulb into boiling water for calibration. He built a J-shaped tube with a spherical bulb fixed to the short horn of the tube, and the top of it was left open (Fig.1.1b). In this thermometer the atmospheric pressure acted against the pressure of the air pocket entrapped in the bulb, but this problem was solved by summing the heights of two mercury columns: i.e. the thermometer and barometer readings. In the Amontons thermometer the boiling point was 73 Paris inches, 28 of them due to the atmospheric pressure and 45 inches to heat. In this calibration, ice melting was found at 51 ½ inches. This instrument was considered to be extremely precise and absolute, useful to calibrate all other kinds of thermometers. This was in theory, because departures were found from one thermometer to another.

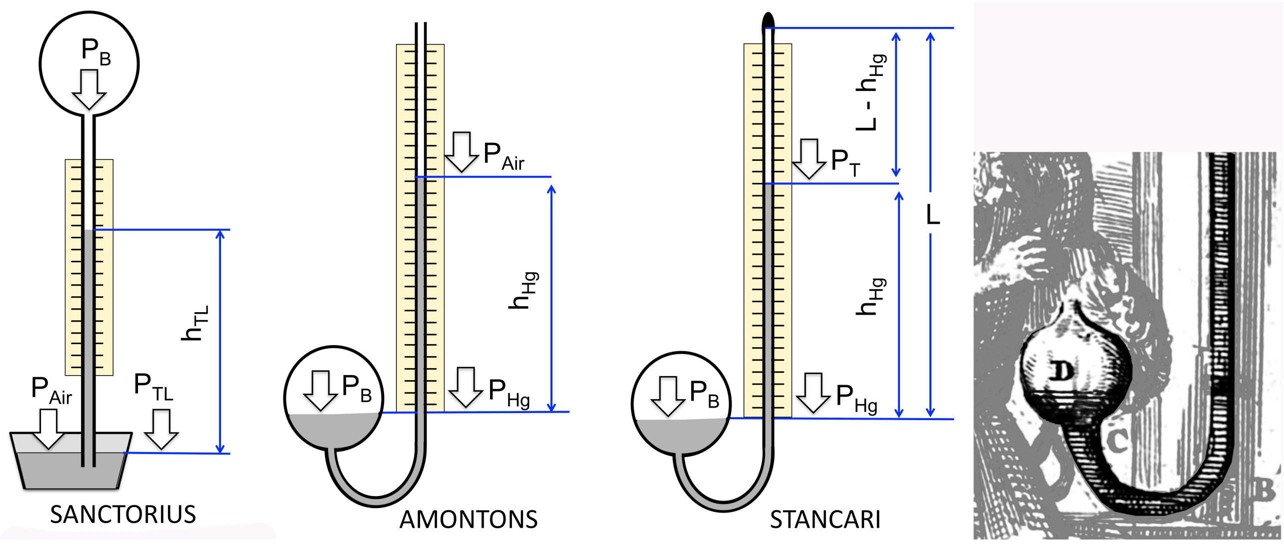

Fig.1.1 Operating principle of early air thermometers: (a) Sanctorius Thermoscope where the pressure in the bulb P_B plus the pressure of the thermometric liquid P_{TL} counteract the atmospheric pressure P_{Air}; (b) Amontons Thermometer where the pressure in the bulb P_B counteracts the pressure of the mercury column P_{Hg} plus the atmospheric pressure P_{Air}; (c) Stancari Thermometer where the pressure in the bulb P_B counteracts the pressure of the mercury column P_{Hg} plus the small pressure P_T of the saturated vapour and some air entrapped on the top of the tube; the atmospheric pressure has been excluded; (d) In the Stancari Thermometer the spherical bulb was ¾ filled of air (detail after Dalencé, i.e. D*** 1707)

However, the Amontons thermometer presented a number of unresolved problems, e.g.: the air pocket was compressed to increase sensitivity, but this caused the condensation of vapour inside, changing the instrument response; it was not sufficient to use heat and fire to remove moisture from air. In particular, calibration was made without knowing the influence of the atmospheric pressure on the boiling point; the barometric readings were not corrected for temperature, elevation and latitude; only the bulb with the air pocket was plunged into boiling water, but not the tube and the barometer that were at different temperature (Camuffo 2002).

The Stancari thermometer (Fig.1.1c, d) was made independent from the atmospheric pressure by sealing the top of the tube.

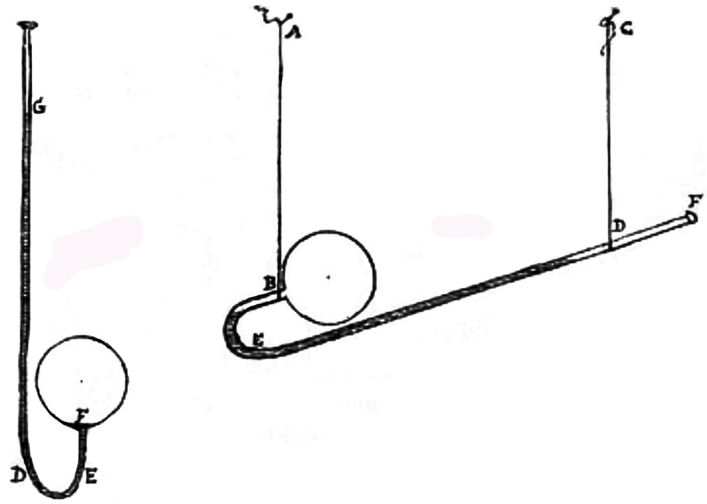

Fig.1.2 The Stancari thermometer in upright position as in the calibration and operation (left). The thermometer kept tilted above the horizontal position when blowing air into the bulb. In this position the counteracting pressure of mercury is reduced to a minimum (right) (Stancari 1708)

After the sphere was joined to the tube, the glass was carefully dried, the thermometer was kept tilted above the horizontal position, and some mercury was introduced from the top. Then, some air was forcedly blown into the bulb with a bellow. The almost horizontal position was necessary to operate with a small overpressure of mercury. These two steps are illustrated in the original manuscript (Stancari 1708) and reported in Fig.1.2.

Estimated error of a previous analysis of this series

Thirty years ago, Comani (1987) recovered the record from the Beccari logs and wrote: "information contained in Beccari's manuscripts indicates that temperature was measured by means of the Amontons thermometer up to 1737." Unfortunately, she disregarded the specification that the thermometer was "Amontons type, improved by Stancari" (Beccari 1724) and its calibration reported in the same handwritten logs. As a consequence, all the technological aspects of this particular thermometer (Stancari 1708; Galeazzi 1746) were neglected. This was a crucial factor. She thought that the thermometer was an Amontons open-tube thermometer and summed the heights of the two mercury columns: the thermometer (h_T) and the barometer (h_B), as illustrated in Fig.1.3. As opposed, the closed-tube Stancari thermometer is a real air thermometer, and the reading is just the height of its mercury column.

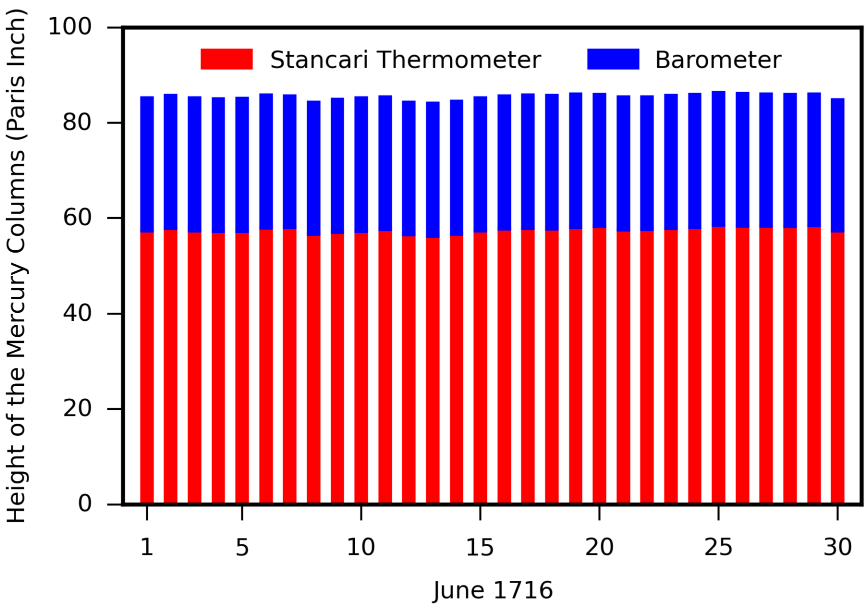

Fig.1.3 Heights of the mercury columns of the Stancari thermometer and the barometer in June 1716. Red bars indicate the heights of the mercury column of the Stancari thermometer; blue bars the barometer. Comani (1987) thought to deal with an Amontons thermometer and made the sum of the two heights

In order to assess and order of magnitude of the possible error, one should consider that, over the year, the Stancari thermometer readings generally lie from 52 to 58 Paris inch (1 inch = 27.07 mm); the barometer from 27 to 28.5 Paris inch; their sum from 79 to 85.5 Paris inch. The variability of the atmospheric pressure had two effects. The most obvious one was the day-by-day pressure change (weather) that introduced a random noise (Fig.1.4). In the Beccari (1724) calibration, one Paris inch corresponds to 4.5° to 7 °C, depending on the particular thermometer (i.e. ST_8 or ST_{12}) and the non-linearity of the scale.

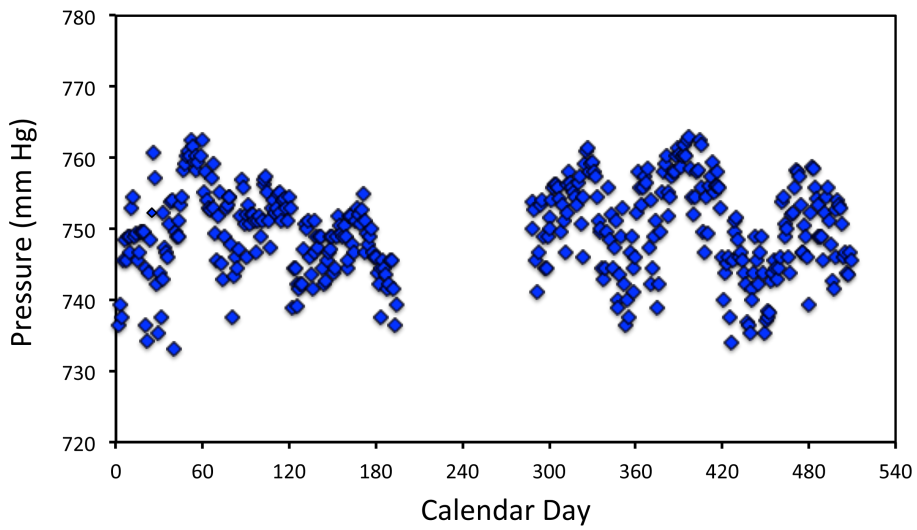

Fig.1.4 Atmospheric pressure readings as reported in the Beccari logs for 1716 and 1717. They are randomly distributed. Gaps are visible in the summer months

The second effect was due to the seasonal cycle that changed very much the average height of the temperature column, but not of the pressure. In the sum (h_T+h_P) of these two atmospheric variables, the relative weight (RW) of the pressure, i.e. RW = $h_P/(h_T+h_P)$, is maximum in winter when the temperature column is smaller and minimum in summer when the temperature column is higher.

The bias reflected this seasonal effect. The difference between the daily temperatures given by the Stancari thermometer following the calibration by Beccari (1724) and the method of evaluation by Comani (1987) has been calculated and reported in Fig.1.5 for the years 1716 and 1717. In this illustration, the daily departure ranges from -1°C in summer to +8°C in winter. It should be noted that the Comani results are limited to yearly resolution, not at daily level as used in this explanatory example. Again, the number of gaps has increased because the comparison has been possible when both the temperature and the pressure readings are available.

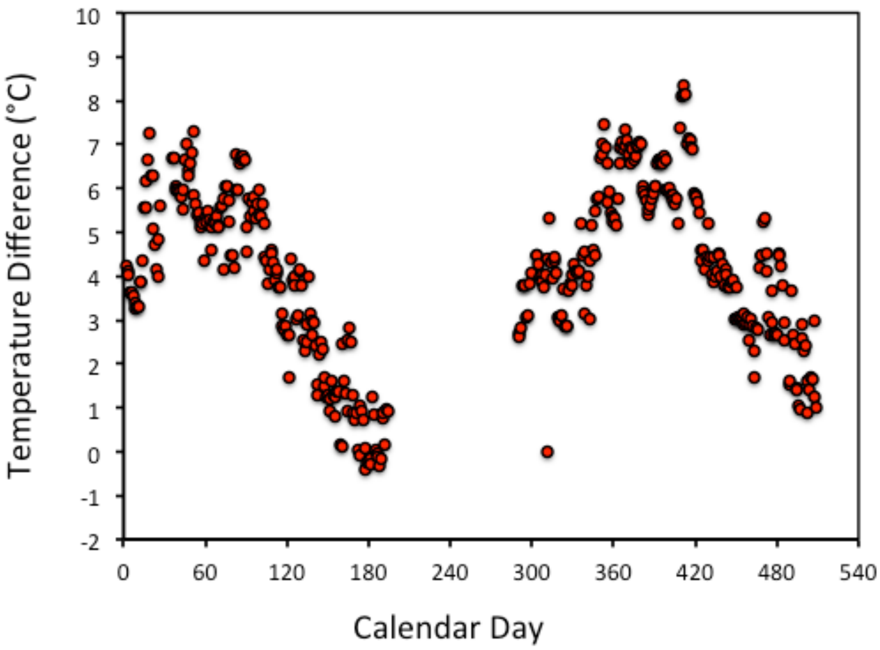

Fig.1.5 Difference between the daily temperatures given by the Stancari thermometer with the Beccari (1724) calibration and the evaluation made following the method by Comani (1987) for 1716 and 1717

The variability introduced by the atmospheric pressure made impossible to interpret the daily and even the monthly records. Yearly averages were better, being less scattered because the differences from one year to another are larger in terms of air temperature than atmospheric pressure. For this reason Comani only published the yearly averages. In the example of Fig.1.5 the bias of the yearly average is some 4°C. The actual difference between the indoor yearly averages obtained following the Beccari instructions and the values in Fig.3 of the Comani paper, is shown in Fig.1.6. However, some of the yearly averages are underestimated, for relevant gaps in summer months.

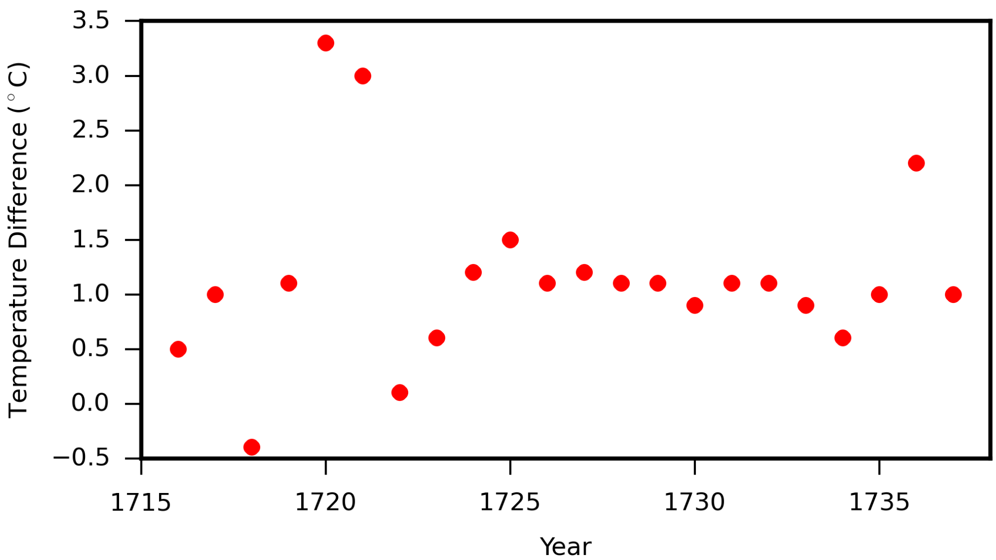

Fig.1.6 Difference between the yearly indoor temperatures given by the Stancari thermometer with the Beccari (1724) calibration and the evaluation made by Comani (1987)

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Online Resource 2

Poggi Palace, seat of the Restless-spirit Academy, later transformed into Institute and Academy of Sciences and Arts

In early 1700s, the governor of Bologna was Count Luigi Ferdinando Marsili, General Deputy of Pope, General of the Vatican Army and supporter of scientific research. With his support, some scientists, i.e.: Jacopo Bartolomeo Beccari, Domenico Gusmano Galeazzi, Eustachio Marchesi, Giovanni Battista Morgagni, Geminiano Rondelli, Vittorio Francesco Stancari and Francesco Maria Zanotti founded the '*Accademia degli Inquieti'* (Restless-spirit Academy) in 1704; Morgagni was the head and Stancari secretary. Headquarter was Poggi Palace, 33 Zamboni Street (see Fig.2.1 and Fig.2.2). They organized a laboratory, an astronomical turret on the roofs, a weather station and built instruments. When Stancari died in 1709, the political situation was uncertain and the Academy was closed and Morgagni left Bologna.

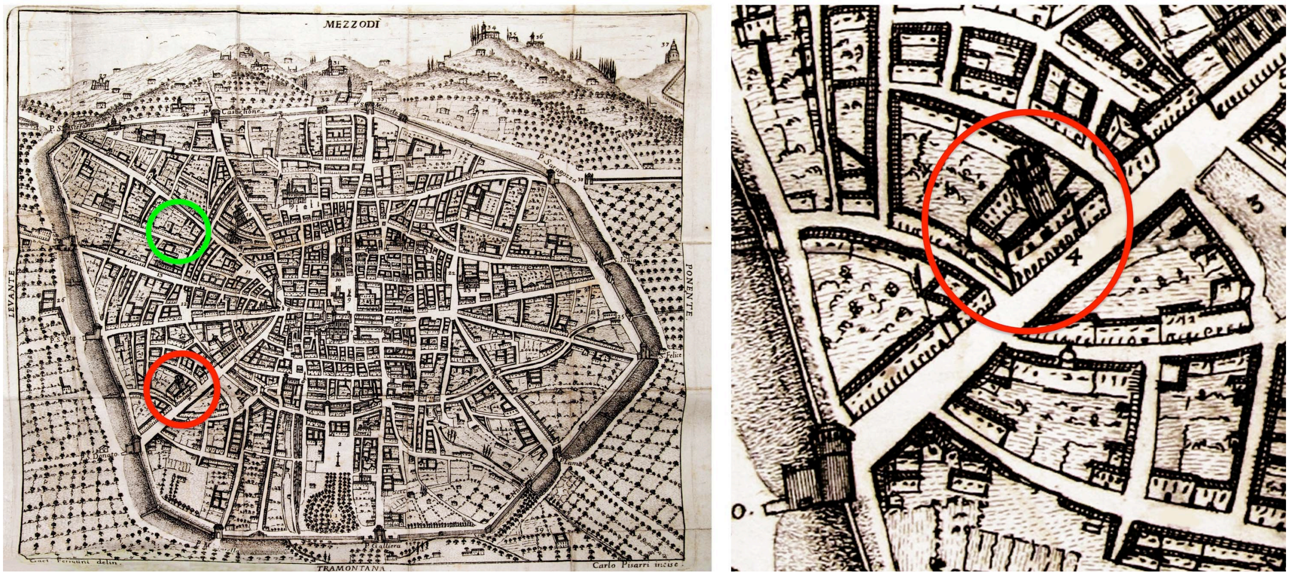

Fig.2.1 Map of Bologna by Gaetano Ferratini, dated 1743, with Poggi Palace seat of IASA inside the red circle; green circle: Beccari's house (left). Detail of Poggi Palace (right). Please note that the map is rotated by 180 deg, i.e. South on the top and West on the right. IASA is on the NE side of the town, close to the walls; the area was characterized by the presence of extensive kitchen gardens

In 1712, in association with the Academic Senate of the Bologna University, Marsili established the Institute and Academy of Sciences and Arts (IASA) that joined the scientific legacy of the '*Accademia degli Inquieti'* to the Clementine Academy of Fine Arts dedicated to Pope Clemens XI. IASA was based in Poggi Palace and became operative in 1714 and included several disciplines: Beccari was named head of natural sciences and Galeazzi his assistant; Zanotti was secretary of the Academy (Bolletti 1751; Zanotti 1739; 1746).

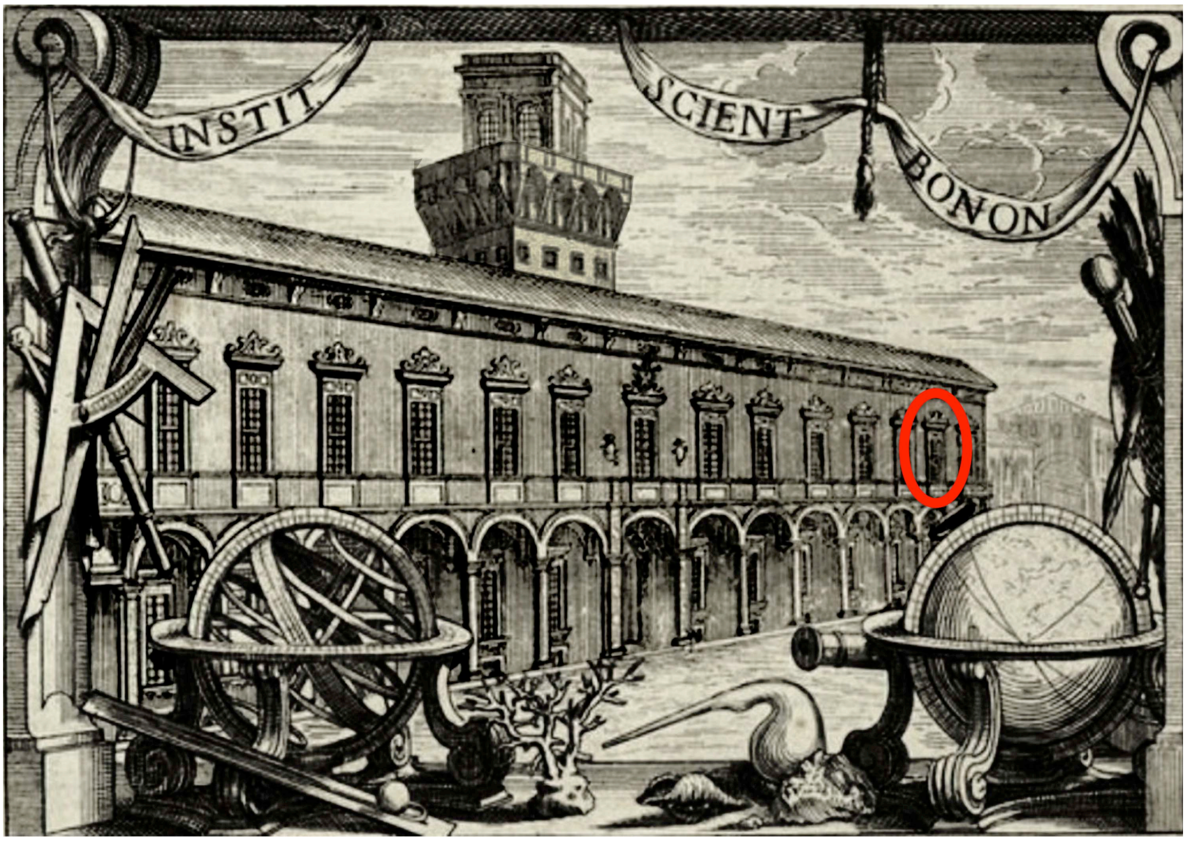

Fig.2.2 Poggi Palace, headquarter of the Restless-spirit Academy, later transformed into Institute and Academy of Sciences and Arts (IASA). The facade is facing NNW (330 deg) and the window of the observation room is encircled (Zanotti 1745). No trees are visible in the street

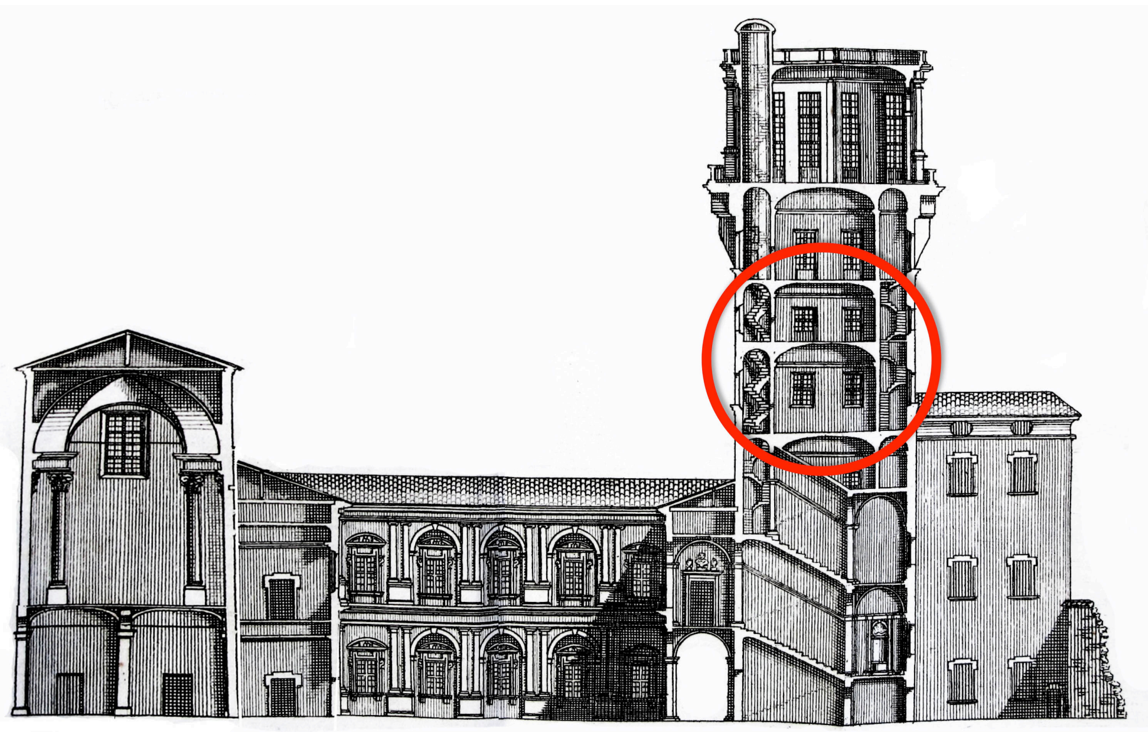

Fig.2.3 Poggi Palace viewed from the internal courtyard and detail of the astronomic tower. The two rooms used as a depository of optical and astronomic instruments are encircled; above the lodgement for the astronomer, i.e. Eustachio Manfredi, and the specula on the top (Bolletti, 1751)

Fig.2.4 The Physics Department, leaded by Beccari (Rooms B,C, D, E, F, cyan), second floor of Poggi Palace. Room F facing NNW (encircled) hosted thermometers and barometers (Bolletti, 1751)

In this building Stancari built his thermometers and Beccari and Galeazzi made the observations from 1715 to 1737. Analysing the data, it is evident, that in 1715, ST_{12} was located in a internal room without ventilation (Room B?) that almost completely dampened the daily temperature cycle. Since 1716 readings were made in a well ventilated room, probably room C, D,E, exposed to SE. In 1720 the thermometer was moved to the cooler Room F exposed to NNW. In 1727 it was moved again in another, less ventilated room (probably on the Tower). These locations are shown in Fig.2.2 to Fig.2.4.

The solar radiation impinging on the external walls (Fig. 2.5) of the mentioned rooms has been calculated for the summer solstice, the equinoxes and the winter solstice in the hypothesis of a clear day and the atmospheric adsorption with standard turbidity (Camuffo 2013). The facade with Room F is hit in the warm season only; the SE side (rooms C,D,E) over the whole year.

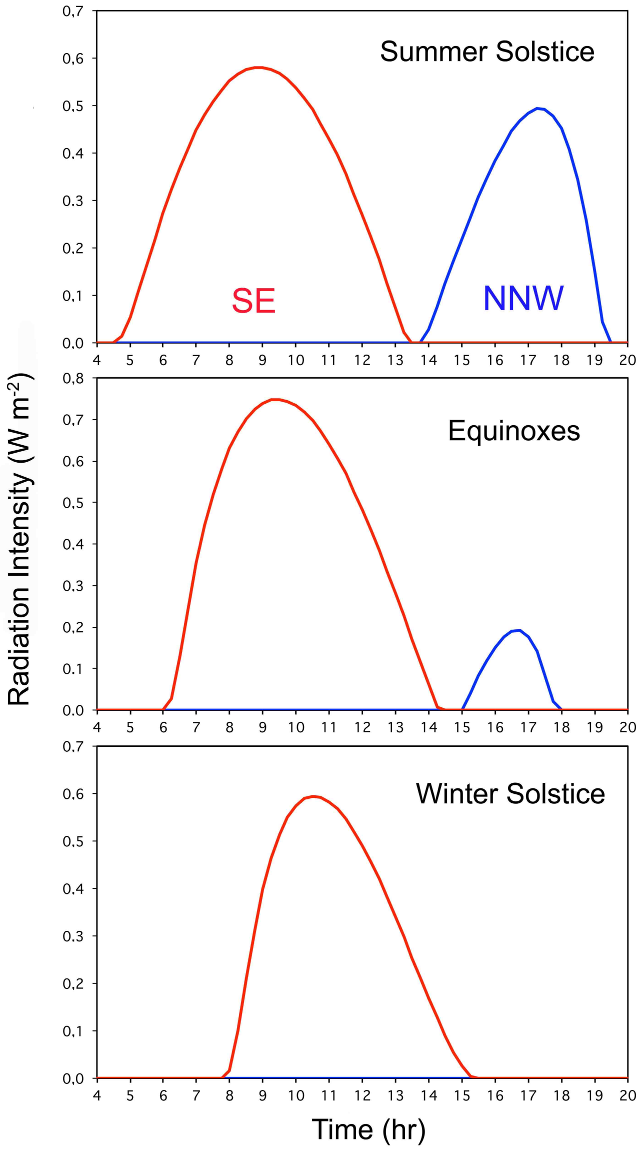

Fig.2.5 Simulation of the solar radiation impinging on Poggi Palace, i.e. the facade (facing NNW, Room F, blue line) and the back (facing SE, Rooms C,D,E, red line). Summer solstice: both the NNW and SE sides are hit, but SE receives more energy. Equinoxes: The radiation on SE is dominant; the NNW side is shortly exposed in the late afternoon. Winter solstice: only the SE side is hit

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Online Resource 3

The Inventors of the Thermometer

Geminiano Rondelli (born 1652, died 1739) mathematician, expert geometry, trigonometry and hydraulic works. He gave the suggestion to seal the top of the tube of the Amontons thermometer to make it independent of the atmospheric pressure.
In 1680 he was appointed lecturer of (Natural) Philosophy at the University of Bologna
In 1682 he was appointed lecturer of Astronomy
In 1689 he had the chair of Mathematics
In 1700 he had the chair of Hydrometry
In 1705 he was appointed Academician (Accademia degli Inquieti, i.e. Restless Academy)
From 1714 to 1721 he was appointed responsible of the Library at IASA
In 1725 he had the chair of military architecture
In 1729 he had the public responsibility water and river management
He was a teacher of Stancari.
Sources: Stancari 1708; Paul 1773; Tiraboschi 1783

Vittorio Francesco Stancari (born 1678, died 1709) mathematician, astronomer, and physicist. He built and studied the closed-tube air thermometer known as Stancari Thermometer.
In 1697, at his home, he started astronomical observations with Eustachio Manfredi and built some instrumentations to this aim (i.e. sextants, quadrants).
In 1701, following Leibniz, he started to study the infinitesimal calculus, and in 1708 was appointed to the first chair of infinitesimal calculus in Italy.
He applied this knowledge to various topics of mathematics, optics, hydrostatics, and acoustics.
In 1704 Eustachio Manfredi nominated Stancari as supervisor of the library, museum and astronomical observatory of the Count Luigi Ferdinando Marsigli where he studied natural history and continued astronomical observations.
In the same year Stancari was graduated Doctor of Philosophy and became secretary of the Accademia degli Inquieti (Restless-spirit Academy) of Bologna until his death.
In 1707 Stancari with Eustachio Manfredi discovered a comet.
Sickly since 1708 for nocturnal observations, he died in 1709 at the end of the extremely severe winter
Sources: Manfredi 1713: Zeno and Zeno 1714.

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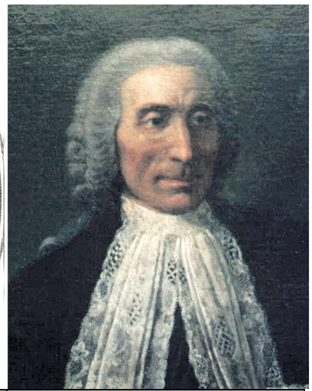
The Observers



Jacopo Bartolomeo Beccari	**Domenico Maria Gusmano Galeazzi**	**Eustachio Manfredi**	**Eustachio Zanotti**
Coordinated the research; observed in 1715	Observed: 1716-1726	Director of the Specula	Observed: 1727-1737

Jacopo Bartolomeo Beccari (born 1682, died 1766; Fig.3.1a) was one of the most leading scientists in Bologna in the first half of the eighteenth century.
He started and coordinated a long series of air temperature, pressure and other weather observations in Bologna: in 1715 he took readings with the Stancari thermometer, and afterwards with other instruments from 1723 to 1766, including the very last day of his life.
In 1704 he was graduated Doctor of Philosophy and Medicine; he became member of the *Accademia degli Inquieti* (Restless-spirit Academy) of Bologna and had the chair of Natural History.
In 1709 he had lectureships in Logic.
In 1711 he was appointed head of the Physics team at the Institute and Academy of Sciences and Arts (IASA) of Bologna with assistant Galeazzi.
In 1712 he was named Professor of Anatomy at the University of Bologna.
In 1714 he was appointed to the chair of Experimental Physics at IASA.
In 1724 he was elected President of the Academy of Sciences, Bologna and in 1728 member of the Royal Society, London. In 1737 he passed from the chair of Physics to the first chair in Chemistry in Italy. He also studied the action of light on silver salts and discovered the gluten in wheat flour.
In 1740 he became member of the Benedictine (in honour of Pope Benedict XIV) Academy. In 1749, after 40 year of teaching, he was named Emeritus Professor and could continue teaching at home.
In 1750 he was elected President of IASA.
Sources: Mazzuchelli 1760; Scarselli 1766; Fantuzzi 1782.

Domenico Maria Gusmano Galeazzi (born 1686, died 1775; Fig.3.1b) was graduated Doctor of Philosophy and Medicine in 1709.
In 1711 he was named Assistant Professor of Experimental Physics, i.e. co-worker of Beccari, at IASA.
In 1714 he went to Paris, where he met Giacomo Filippo Maraldi, Jacques Cassini, Louis Lémery, Nicolas Malebranche, René Antoine Ferchault de Réaumur, and other men of science and attended meetings of the Académie Royale des Sciences.

In 1716 he became lecturer of Philosophy and started the readings of the Stancari thermometer at IASA.
In 1734, when Beccari was appointed to the chair of Chemistry, he had the chair of Experimental Physics, with assistant Paolo Battista Balbi.
Galeazzi made geological observations and progresses in entomology and medicine; he discovered intestinal gland and ascertained the presence of iron in the human blood.
In 1739 he was appointed lecturer of Anatomy and was committed to work at home and the Anatomic Theatre. For this reason he left IASA, but stopped temperature readings in January 7th 1738.
He wrote a paper on the technology of the Stancari thermometers and performed some tests concerning the condensation inside the bulb.
Sources: Galeazzi 1746; Fantuzzi 1784; Medici 1857.

Eustachio Manfredi (born 1674, died 1739, Fig.3.1c) was graduated in Law; in 1698 he was appointed to the chair of Mathematics; in 1704 superintendent to the waters; in 1711 director of the Astronomical Observatory. In 1726 he became member of the French Academy of Sciences, Paris, and in 1729 of the Royal Society, London. He was charged for geography, rivers and waters. He was the founder of the Restless-Spirit Academy, good friend and colleague of Stancari, Beccari and Galeazzi. With Stancari he discovered a comet in 1707. He cared the posthumous edition of the Stancari papers. Manfredi was died on February 13th, 1739. We suppose that Manfredi charged his assistant Eustachio Zanotti for the readings in the Tower from 1727 to January 7th 1738.
Source: Cavazzoni Zanotti 1745

Eustachio Zanotti (born 1709, died 1782; Fig.3.1d) Astronomer, he was the first assistant of Manfredi and became Director of the Astronomical Observatory in 1739, after Manfredi was died. He especially cared comets, polar aurorae, eclipses and other celestial bodies. He was also specialist in rivers and water management, but was not interested in meteorology.

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Online Resource 4

The Logs

Readings of ST_8 and ST_{12} thermometers have been recovered by the original logs. The record of the year 1715 has been found at the Archiginnasio municipal library, Bologna, in the collection entitled to Giacomo Biancani Tazzi. The handwritten document (see Fig.4.1) contains temperature and pressure readings for Bologna taken by Jacopo Bartolomeo Beccari and pressure readings for Florence taken by his brother, the Benedictine Father Johannes Gualbertus Beccari from July 1715 to the end of the year. The record is organized in a tabular form, with columns for: date, observing hour in Italian time, barometer in Paris inches (1 Paris Inch = 27.07 mm), lines in twelfths and fractions, thermometer in inches and lines in twelfths (i.e. °S), and some observations of the sky.

From 1716 to 1737 records are preserved in the library of the Astronomical Observatory of Padua together with further data taken by Beccari from 1716 to 1766. Records are organized in a tabular form, with columns for: date and observing hour, barometer in Paris inches, lines in twelfths and fractions, thermometer in inches, lines in twelfths and fractions of Stancari degrees (°S), wind speed and direction, and some observations of the sky. When Beccari was young, the logs were well handwritten (Fig.4.2 for the year 1716); later the style was worsened.

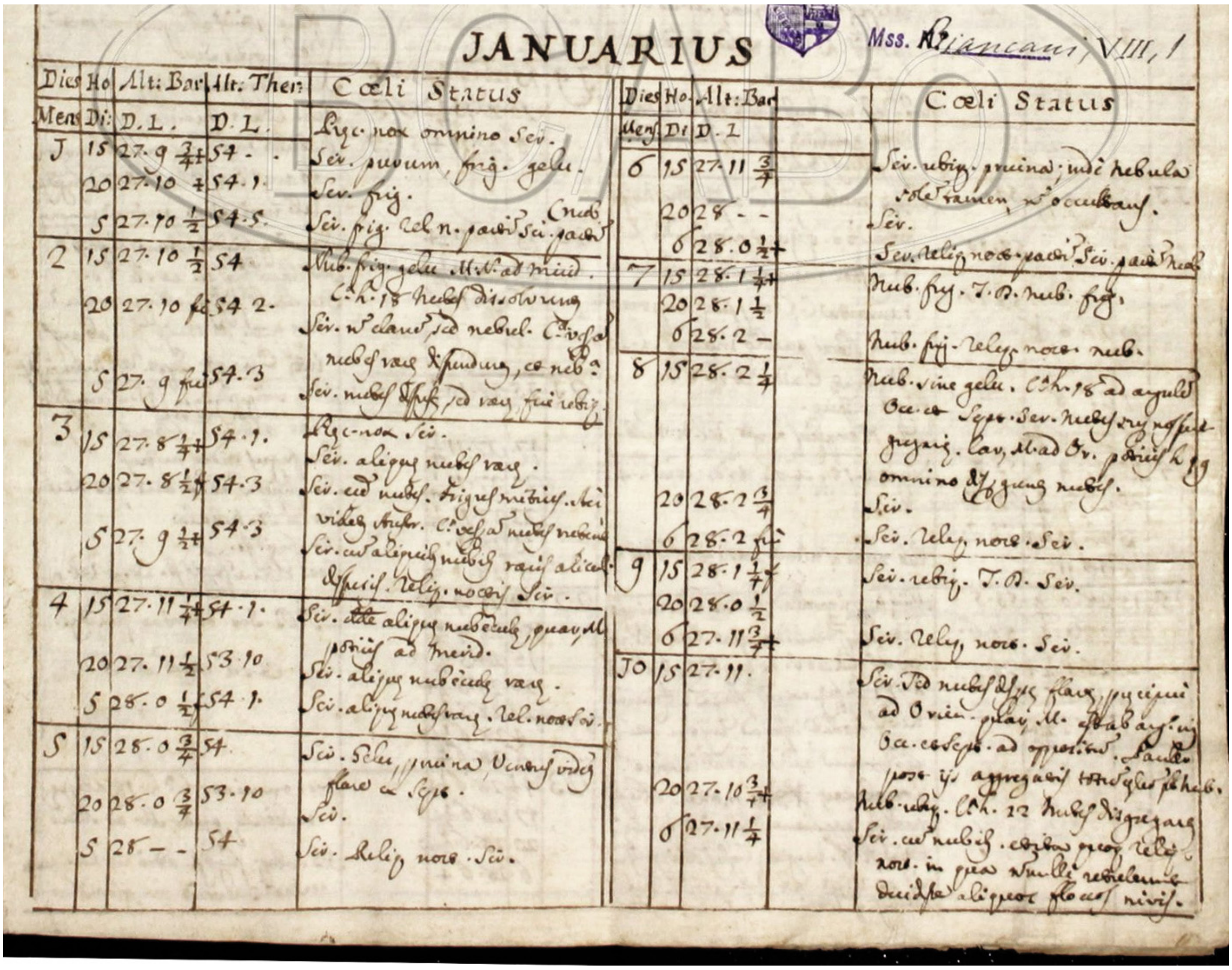

Fig.4.1 The Beccari's 1715 readings entitled "Ephemerides - daily observations of the main atmospheric changes". (By courtesy of the Archiginnasio Library, Bologna)

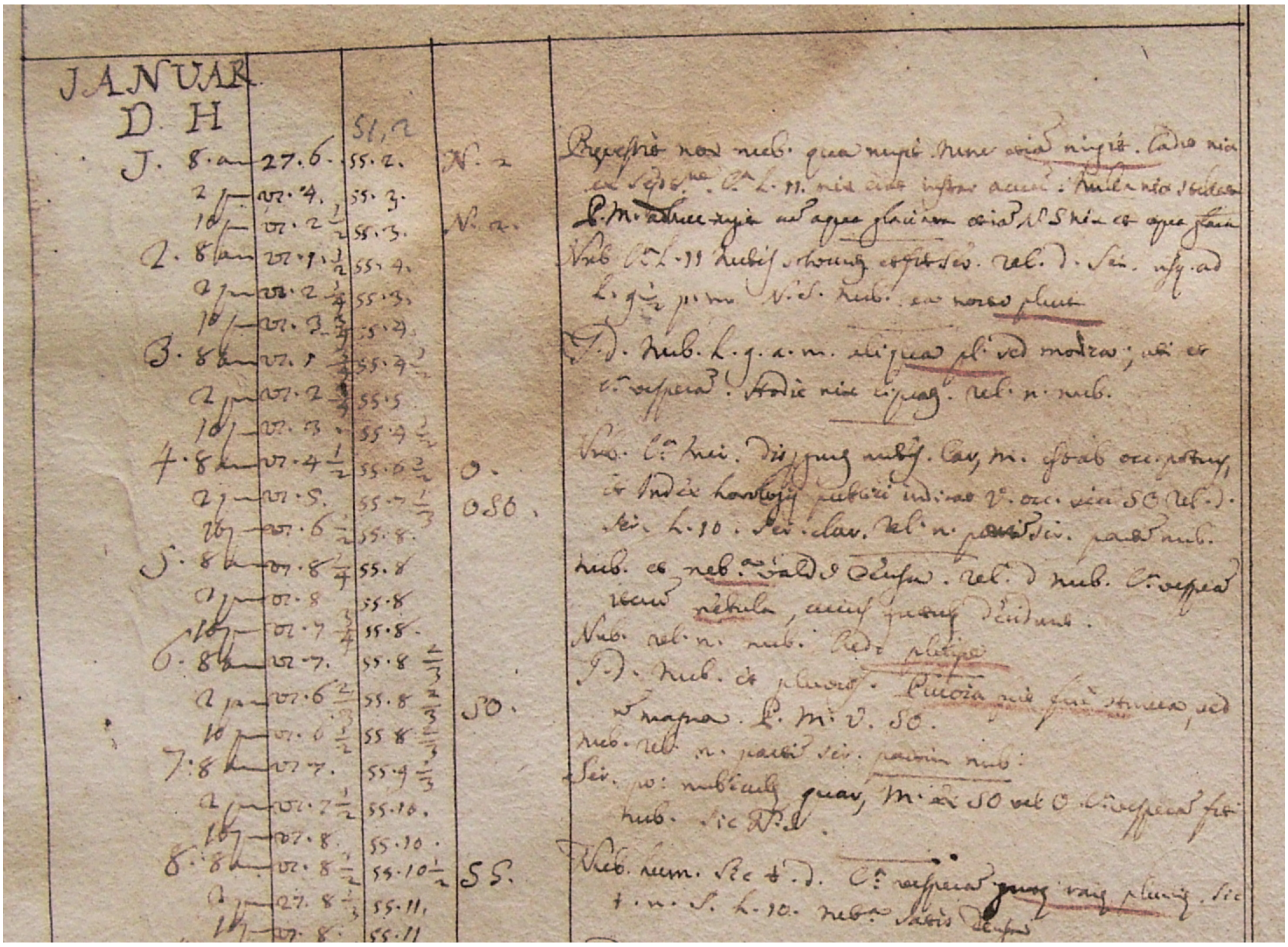

Fig.4.2 Beccari's log of January 1716 including the readings by Galeazzi. (By courtesy of the Library of the Astronomical Observatory, Padua)

Online Resource 5

Missing Readings

Readings were made at 08:00, 14:00 and 22:00. Missing readings are not homogeneous and may be one or more in a day (temporary drawback), or last for consecutive days (observer sick, or out of town). Missed readings are illustrated in Fig.5.1

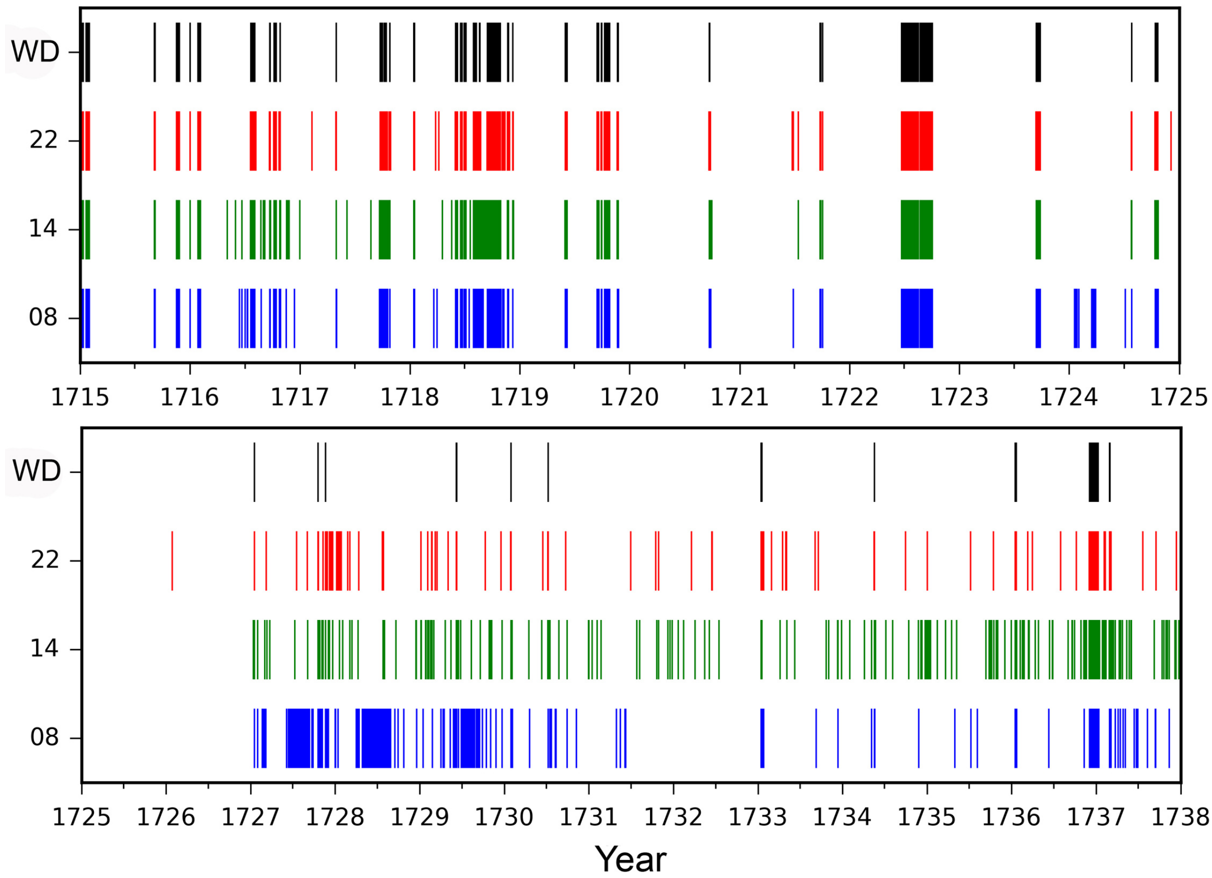

Fig.5.1 Missing readings at 08:00 (blue), 14:00 (green), 22:00 (red) and whole day (WD, black)

From 1716 to 1719 and in 1722 the observer was off in summer, probably for countryside business.

Since 1727 the frequency of missing readings changes, and the most affected time was 08:00, when astronomers sleep after having observed in clear nights (Fig5.2). The analysis of missing readings in correlation with precipitation gives: 17% in precipitation days; 83% no precipitation days. This confirms that most gaps occur in coincidence with astronomic observations in clear nights.

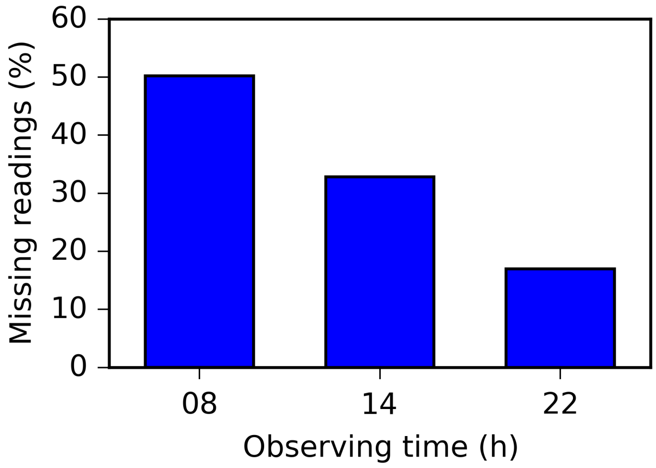

Fig.5.2 How is the total number of missed readings distributed among the three observing times: 08:00, 14:00 and 22:00

Online Resource 6

Mastic and Putty in building Thermometers

The *Accademia del Cimento* (active from 1657 to 1667) built scientific instruments starting with glass items and two kinds of putty, i.e. "*mastic*" and "*fire putty*" (Fig.6.1; Magalotti 1667; Targioni Tozzetti 1780).

"*Mastic*" was composed of resin drops from *Pistacia lentiscus*, i.e. resin of Chios (Baldinucci 1681).

"*Fire putty*" was a mixture of Greek pitch (i.e. colophony or rosin, a resin extracted from pines; it has 75 °C softening point and 100° to 130 °C melting point), turpentine and brick dust, melted over a slow fire (Magalotti 1667; Targioni Tozzetti 1780).

Another popular recipe of "*Fire putty*" was with addition of bee wax (62°- 65°C melting point), and the use of fine powder of lime or chalk (Baldinucci 1681).

Stancari was aware of this traditional technology. One century later, Flaugergues (1813) built some Stancari thermometers using either "*glazing putty"* (i.e. linseed oil and finely powdered chalk), or yellow wax (Flaugergues 1810). Glazing putty is temperature sensitive and in particular wax melts at 62-64°C. Probably for this reason Flaugergues could not calibrate his thermometers. In his study on the drift of the fixed points he used thermometers built by Pierre Casati (Lussac 1822).

All of the above binders are temperature sensitive and are softened or even melted at boiling water temperature. If the bulb is plunged in boiling water, the high pressure of the air pocket inside the bulb (around 2 atmospheres) will violently separate the tube from bulb, making impossible the calibration.

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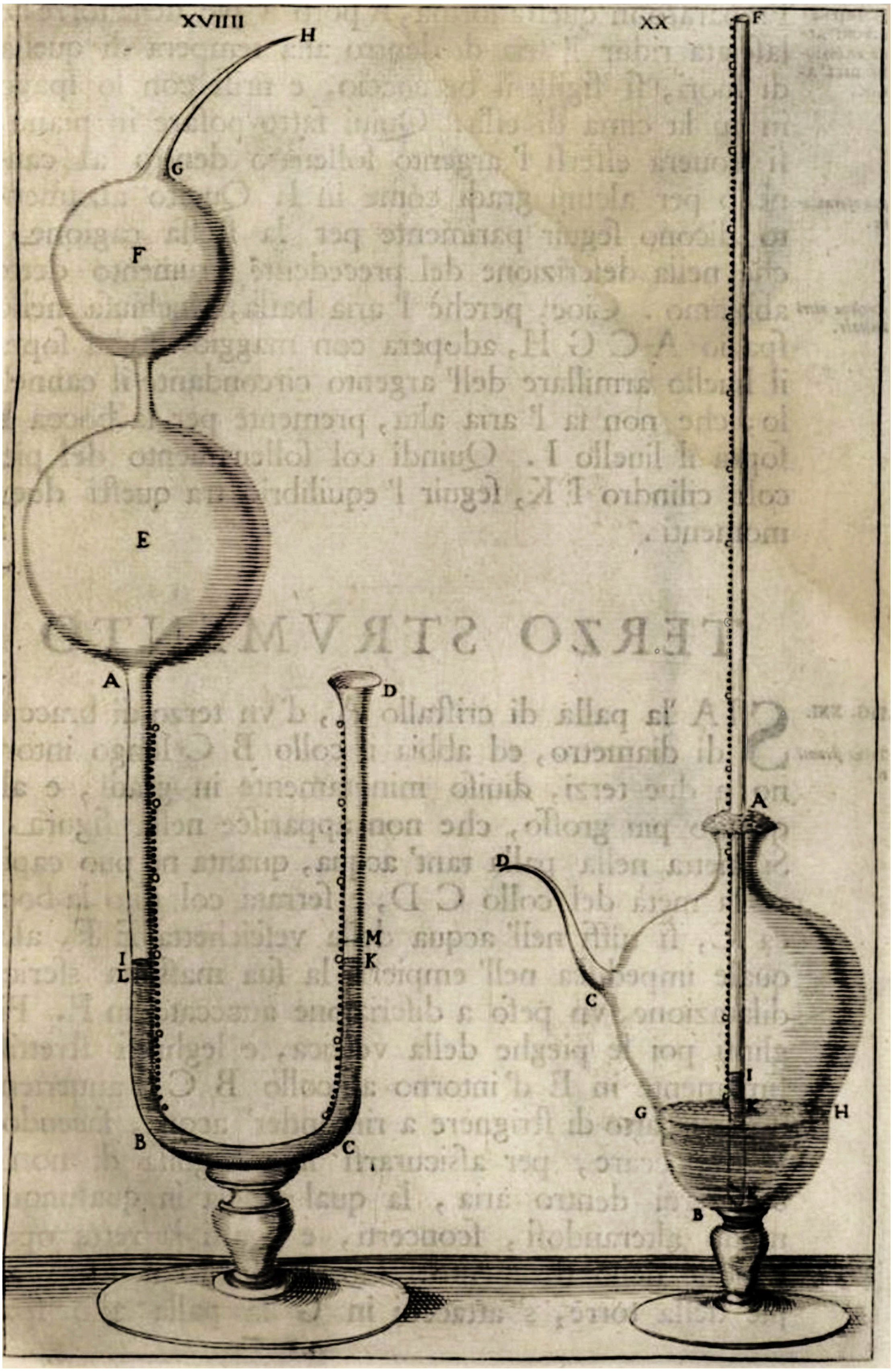

Fig.6.1 Scientific instruments made by the *Accademia del Cimento* using glasswork and "*mastic*" or "*fire putty*" (Magalotti 1667)

Online Resource 7

Air on the top of the tube

In early thermometers with the tube hermetically closed on top, and the free volume inside the tube above the column was filled with the saturated vapour of the thermometric liquid. However, some air could remain entrapped inside or was deliberately left inside claiming to reduce the evaporation of the thermometric liquid.

The situation was known: De Luc (1772) gave careful instructions and Maxwell (1871) made a clear summary, i.e. “There is now nothing in the tube but mercury, and when the mercury contracts so as to leave a space above it, this space is either empty of all gross matter, or contains only the vapour of mercury. If, in spite of all our precautions, there is still some air in the tube, this can easily be ascertained by inverting the thermometer and letting some of the mercury glide towards the end of the tube. If the instrument is perfect, it will reach the end of the tube and completely fill it. If there is air in the tube the air will form an elastic cushion, which will prevent the mercury from reaching the end of the tube, and will be seen in the form of a small bubble.”

At high temperatures, the free volume is reduced and, if some air has been left entrapped, its pressure will increase, exerting a force that counteracts the rise of the liquid column. In the case of a liquid-in-glass thermometer (e.g. Florentine, Réaumur) this was not a problem because the bulb was filled with liquid. Liquids are almost incompressible and the effect of the rarefied air left on the top of the tube was considered negligible, i.e. “the air that remains above the liquid has neither the density not the spring of ordinary air” (Réaumur 1730).

However, in the ST this makes a substantial difference because the column of mercury was moved by the expansion of the air pocket in the bulb, having pressure P_B (Fig.7.1). This equals the pressure P_{Hg} due to the height h_{Hg} of the mercury column in the tube plus the pressure P_T of the air left on the free volume V_T on the top of the tube, i.e. $V_T = (L - h_{Hg})\,\pi r_T^2$, where L is the length of the tube and r_T its radius. In practice,

$$P_B = P_{Hg} + P_T = \rho g h_{Hg} + \frac{n_{air} R T}{(L - h_{Hg})\pi\, r_T{}^2}$$

where ρ is the density of mercury, g the Earth acceleration, n_{air}, the number of moles of air entrapped on the top, R the gas constant.

If some air was left inside, the deviation from linearity becomes especially strong when the temperature approaches the boiling point, because the difference $L - h_{Hg}$ tends towards 0. In addition, the departure is proportional to n_{air}, and is only relevant for a large parcel of entrapped air.

In the specific case of the ST used in Bologna, the temperature was generally $T < 30$°C and $L - h_{Hg} > {}^2/_3\, L$ that excludes a relevant bias.

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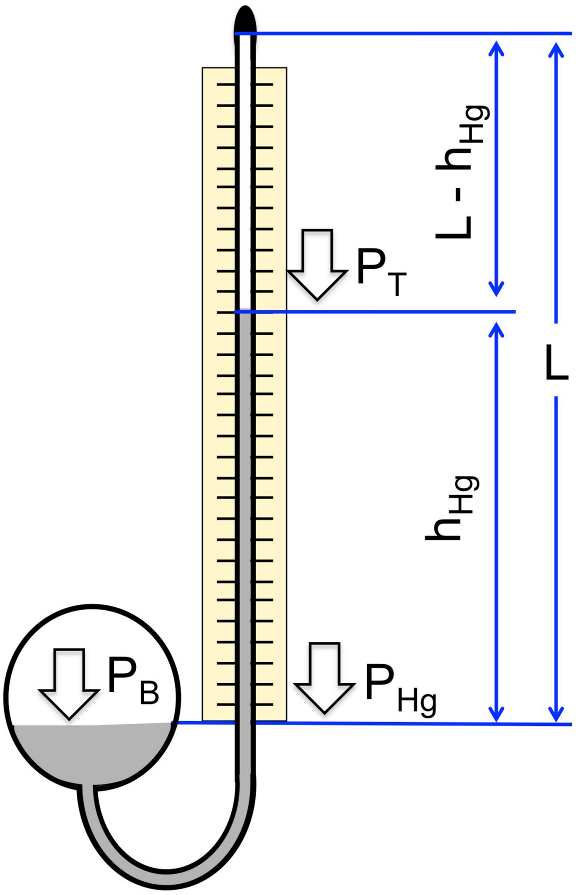

Fig.7.1 The pressure (P_B) inside the spherical bulb and the two counteracting pressures (P_T, P_{hHg}) in the tube of the Stancari thermometers

Online Resource 8

Departure from Linearity: the Spherical Bulb

When the bulb is a sphere, the area of the free surface of mercury changes with the cross section of the sphere.

A small increase of temperature ΔT in the bulb determines a small increase of the air pocket volume ΔV

$$\Delta V = \Delta h_S \, \pi \, r_a^2$$

where r_a is the radius of the actual horizontal section of the sphere, as shown in Fig.8.1.

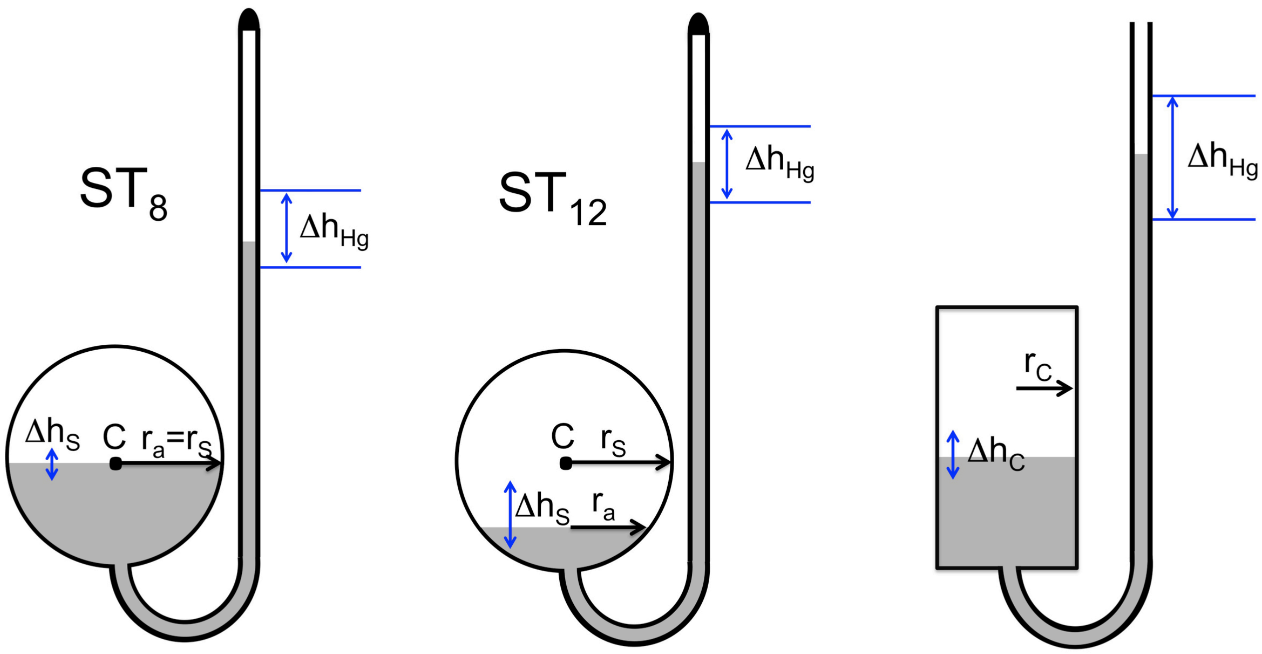

Fig.8.1 Departure from linearity of spherical bulbs. Left: When the air pocket fills the upper half of the sphere, as in ST_8, the free mercury surface moves up and down across the centre C of the sphere without changing too much its surface area. The radius r_a of the free mercury surface is almost equal to the radius of the sphere r_s. A small displacement Δh_S of the mercury in the sphere will cause a large displacement Δh_{Hg} of the mercury top in the tube. Middle: When the air pocket reaches the lower part of the sphere, as in ST_{12}, the area of the free mercury surface becomes smaller and smaller and $r_a << r_s$. Larger displacements Δh_S of the mercury in the sphere are needed to provide the above displacement Δh_{Hg} in the tube. The curvature of the sphere is responsible for an apparent acceleration at higher temperatures. Right: In a cylindrical bulb, the radius r_C of the free mercury surface is constant and a small displacement Δh_C of the mercury will always be followed by the same displacement Δh_{Hg} in the tube.

The air expansion will move an equal volume of mercury into the tube, and the height of the mercury column will increase by Δh_{Hg}. The height increase is determined by equalling the two volumes, i.e.

$$\Delta h_S \pi r_a^2 = \Delta h_{Hg} \pi r_T^2.$$

In other terms, inside the sphere, ΔT will cause an expansion ΔV and a pressure increase

$$\Delta P = \rho g (\Delta h_S + \Delta h_{Hg}).$$

The ratio between the displacements at either topping sides of the mercury (i.e. Δh_{Hg} in the tube and Δh_S in the spherical bulb) is

$$\Delta h_{Hg} / \Delta h_S = (r_a/r_T)^2$$

i.e. the ratio of the horizontal cross sections of the spherical bulb (πr_a^2 large and variable) and the tube (πr_T^2 small and constant). The same holds when T decreases.

Correction of the Departure from Linearity

The readings of ST_8 and ST_{12} have been plotted versus the Little Florentine Thermometer (LFT) read by Beccari over the common periods, i.e. ST_8 from 1723 to 1726 and ST_{12} from 1727 to 1737.

The comparability of readings taken with the LFT was based on the same response of the instruments that are all identical between them, being an accurate replica of the same prototype. As the LFT was the first thermometer able to take quantitative measurements, the discovery of the fixed points usable for calibration occurred later. However, a rough control of the scale was made by plunging the thermometer into the cold water of the Arno River and exposing it to the summer sunshine in Florence and was limited to the usual range in temperate latitudes (Magalotti 1767; Camuffo and Bertolin 2012).

The LFT is a spirit-in-glass thermometer filled with spirit of wine. Although ethyl alcohol has a strong deviation from linearity, reaching -3°C at 20°C, the calibration was made with the lower reference a few degrees above 0°C and the upper point at about 35°C. The lower point had a negligible departure, and the upper point was close to the maximum departure. However, a linear interpolation between these two reference points reduced the departure from calibration very much and the output was linearized (Camuffo and della Valle 2016).

The ST_8 thermometer shows a linear relationship with LFT (Fig.8.2) with equation

$$ST_8 \,(°S) = a\,X + b$$

where $a = 3.90$ °S °G^{-1}, $b = -202.27$ °S; X represents the LFT readings in °G; $R^2 = 0.972$.

The ST_{12} thermometer shows a parabolic relationship with LFT (Fig.8.3). The non-linearity was corrected with a second-order equation obtained after comparison with the parallel readings of the LFT, i.e.:

$$ST_{12} \,(°S) = a\,X^2 + b\,X + c$$

where $a = 0.27$ °S °G^{-2}, $b = -25.7$ °S °G^{-1}, $c = 620.0$ °S and $R^2 = 0.991$.

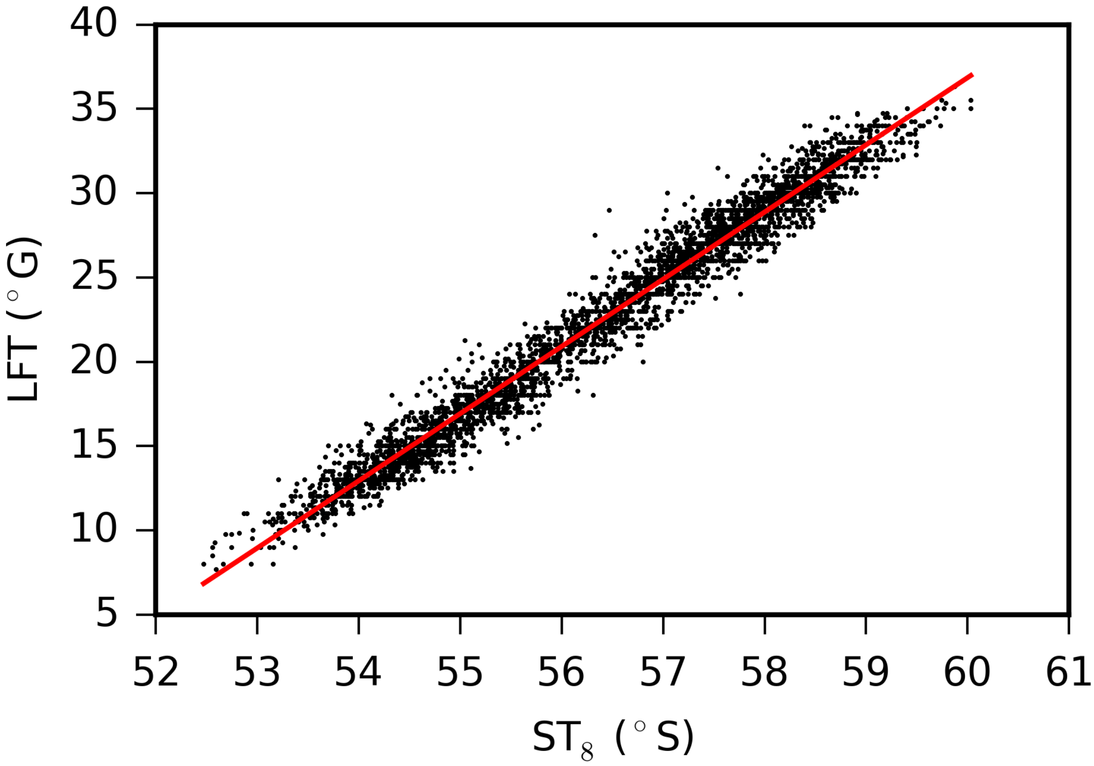

Fig.8.2 Linearity of ST_8, made evident by the comparison of ST_8 (°S) versus LFT(°G) over the 1723-1726 common period

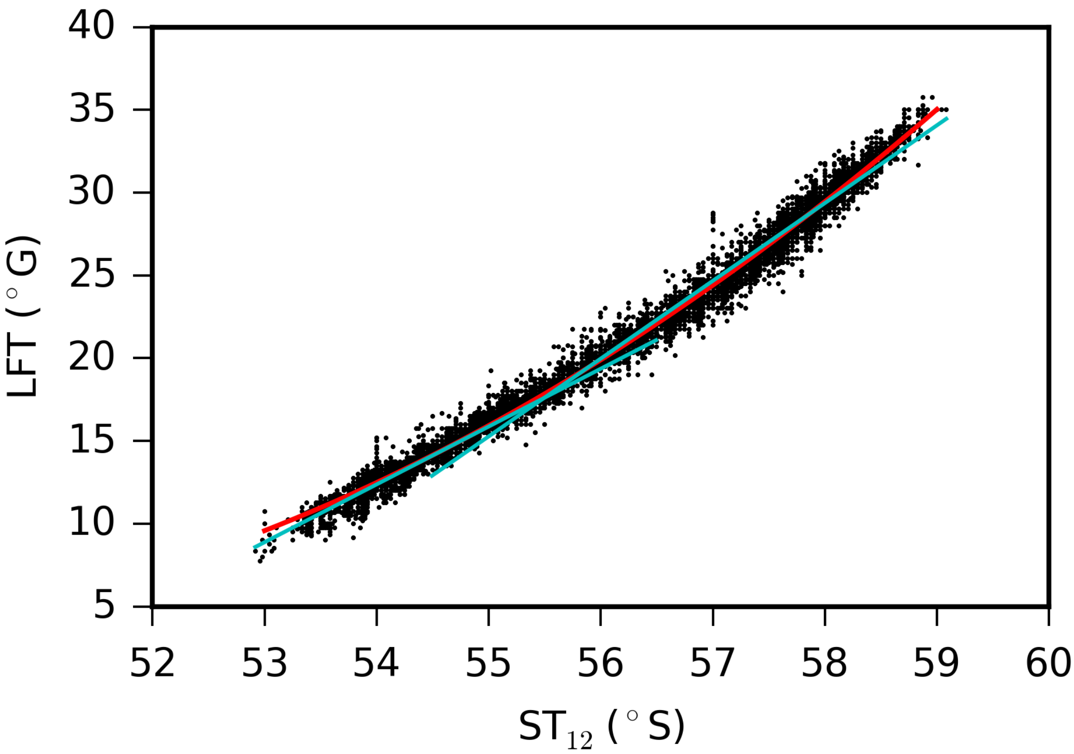

Fig.8.3 Non-linearity of ST_{12}, made evident by the comparison of ST_{12} (°S) versus LFT(°G) over the 1727-1737 common period. Red line: second-order interpolation; cyan lines: first-order interpolation of the readings above and below the intersection point

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Online Resource 9

Poggi Palace: indoor - outdoor Temperature Difference

The two Stancari thermometers were operated indoors from 1715 to1737 and in that period no other parallel records were taken outside to determine the indoor-outdoor transfer function for Poggi Palace and transform the indoor record into outdoor values.

However, as we will show in a future paper, there was a fortunate coincidence that Jacopo Bartolomeo Beccari, head of the team, made parallel records with five additional thermometers from 1723 to 18th January 1766, the last day of his life. He gave no information about the thermometer scales and where the thermometers were located. However, in his obituary speech (Scarselli 1766) we found that he observed at home, and the analysis of the temperature differences at the various observing times, i.e. 8:00, 14:00 and 22:00, shown that all thermometers were kept in the same room, except for one Réaumur thermometer that was kept outside from 1742.

This gave the possibility to recognize the indoor-outdoor transfer function for the Beccari house and apply it to the records of the other four thermometers used in the same room. However, they were unusual thermometers, and required time to find the key to interpret their scales, as will be explained in another paper. One of these thermometers operated since 1723. It was then possible to calculate the outdoor temperature over the whole observation period and compare it with the parallel readings taken inside Poggi Palace over the common period and find the transfer function for this building.

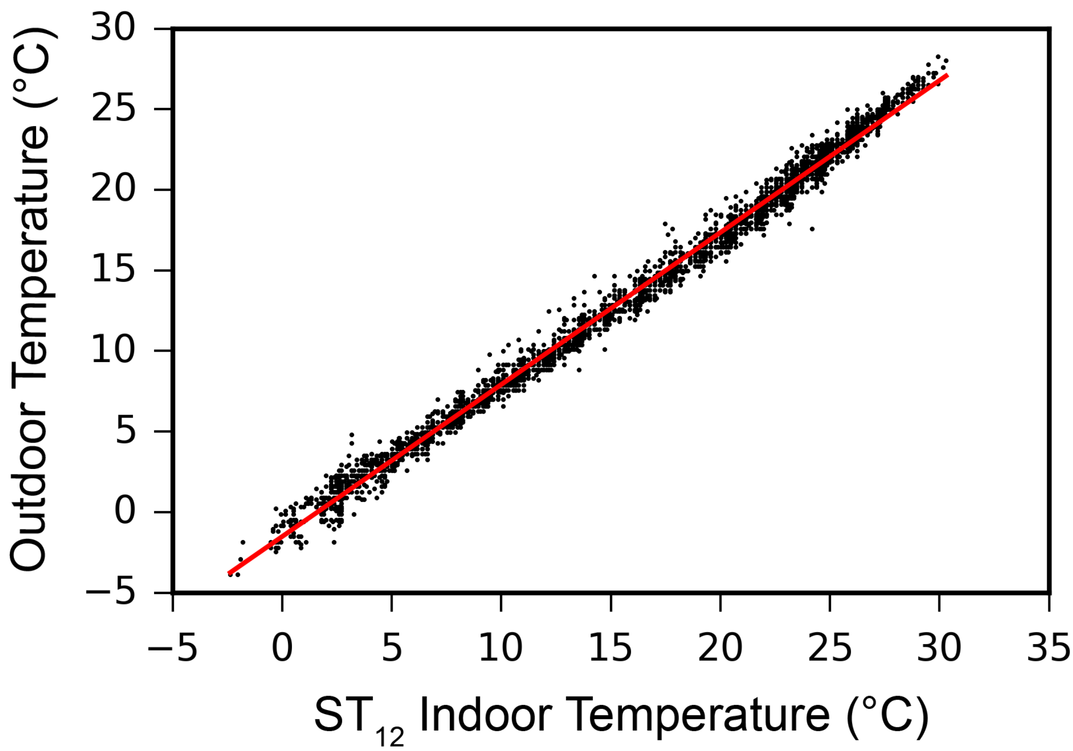

Fig.9.1 Comparison between the readings taken with ST_{12} inside Poggi Palace and the external temperature calculated after the Beccari records

The best-fit of this comparison (Fig.9.1) is a straight line with equation

$$T_{out} = a\, T_{in} + b$$

where T_{out} and T_{in} are the outdoor and indoor temperatures; $a = 0.943$ and $b = -1.509$ °C the transfer coefficients for Poggi Palace and $R^2 = 0.988$ the determination coefficient. As usual, the indoor temperature is higher, and the difference with the exterior is

$$T_{in} - T_{out} = (1-a)T_{in} - b.$$

The average indoor - outdoor difference for Poggi Palace is 2.4°C, very close to the value found for the Beccari house. This is not surprising because the indoor - outdoor difference is not representative of the usual indoor building climate, but of the room prepared for indoor observations (Cocheo and Camuffo 2002). This climate is not only determined by the building envelope, but especially by the room ventilation operated before each reading, and it is obvious that the Beccari's Pupils (i.e. Galeazzi and Zanotti) and Beccari himself strictly followed the same ventilation protocol obtaining similar results.

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