Refractive sundials in Italy

Lino Colombo

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Preface

When I wrote the article about the history of the refractive sundials, I was puzzled and surprised to find a copy of the clock attributed to Hartmann in the Museum of Science and Technology of Madrid. Since antiques dealers sell often fakes, built in some way, I thought that the dial studied by Lino Colombo was a fake and that the original clock was the one exhibited in the Spanish museum. But I was wrong, even if the facts, at that time, seemed to confirm what I thought.

Some time ago Lino wrote me saying that he had something to tell me. Everything he explained me is contained in the subsequent lines (which correct what I previously misunderstood). The following article is a complete well-documented research stating important founding elements in the history of refractive sundials in Europe and mainly in Italy, looking at the few specimen founded.

Colombo not only reveals the 'mystery' of the Hartmann dial but goes personally to Urbino to study the 'bowl' specimen of the roof-garden of Palazzo di Urbino and discoverers something relevant. By starting from documents he raises new doubts and questions on specimens collected in other museums. The friend and collaborator Lino Colombo, is once again an expert and competent researcher in the history of these instruments.

Nicola Severino

I have to write the following article about refractive sundials in order to correct the statements concerning me written by Nicola Severino in the article *Storia dell'orologio a rifrazione* (published on March 2009 on the site www.nicolaseverino.it), more precisely in the paragraph entitled 'L'orologio di Hartmann in Italia: originale, un falso o una svista?'

In the first number of the magazine 'Gnomonica', published by Severino in September 1998, I announced the discovery and restoration of a refractive sundial in the shape of an hemispheric bowl, signed by Georg Hatmann (latinized in Georgius Hartman) dated 1547 (L. COLOMBO, *La meridiana di Acaz. Un orologio solare a rifrazione di Georg Hartmann datato 1547*, "Gnomonica", 1, settembre 1998, pp. 13-17). That bowl isn't a fake, but the original one kept in the Museo Nacional de Cienca y Tecnologia di Madrid.

At this point of the long and for me regrettable story, I would like to update what I wrote in the previous quoted article, in order to include all my recent discoveries, flourished again in the last years thanks to Stefano Pagliaroli, philologist of the university of Verona (he incited my studies with doubts, questions and also gave me a lot of bibliographical material attached with very detailed pictures).

But let's speak about the Hartman bowl

This metallic bowl was probably discovered by a second-hand dealer of Varese in a depot in Lugano and was sold, in April 1998, for little money, to an antiques dealer who gave it to me so that I could study it.

It was so oxidized and dirty that it was difficult to imagine how it worked: the interior lines couldn't be identified, it was necessary a three day-cleaning.
In the bottom hole for the compass, the second-hand dealer had put a big bolt (in order to fix the bowl to a chromium metal lion) that unfortunately scratched the surface.
I rebuilt the missing gnomon using the spoke of a motorbike.
Then I inserted a modern compass in the hole and I filled the bowl with water in order to understand how that worked as the sun moves across the sky.
I could keep the bowl at home in Dairago (Milan) for no more than a month and in that period I wrote the article published in "Gnomonica".
In the meantime the antiques dealer tried to sell the bowl to some Italian collectors, but the negotiations were unsuccessful: he asked 40 million-lira for it; instead I was vainly waiting for the answer of an important museum where I communicated the discovery.
In the end, using the refraction of the light (with a projector) in a bowl full of water, I could show 'the miracle of Acaz' to my fellow-citizens during a conference at my town council on May 29th 1998. After that I had to give back the bowl to the antiques dealer.
The sundial was brought to London together with my article. At the end of 1998 the leaflet advertising one of the Sotheby auction (planned for April 2009) showed the bowl of Hartmann on the front page. It was knocked down at 90000 pounds on April 27th 1999 to an anonymous buyer.
I was invited, but I didn't take part, in the IX Seminario di Gnomonica (that took place at San Felice del Benaco on March 26th-28th 1999) for a talk about the sundial of Acaz. Don Alberto Cintio asked me if he could read my article in public and after that he exposed the mathematical formulas useful to compute and build refractive sundials, also called anacalstic.
The Museo Nacional de Cienca y Tecnologia of Madrid bought the bowl, if I have got the correct information, in summer 1999 by the shrewd buyer of the Sotheby auction, for about a thousand million lire. The shrewd buyer was advantaged by A. Turner that, in the catalogue of the auction and in a subsequent article, asserted that Hartmann's sundial was built for northern-central Spain (and not for Rome, as my research maintains) and that a probable client was Emperor Charles V or a bishop close to him that was in Germany in 1547 (A.J TURNER, *A biblical miracle in a Renaissance sundial*, 'Bulletin of Scientific Instrument Society' n. 61, June 1999, pp 11-14).

The bowl is now in Madrid and it's nearly an exact copy of the one kept in Museo de Santa Cruz in Toledo, this one in a good state with a shining gilding. A third Hartmann refractive bowl, similar to the previous ones, dated 1548 and built for the latitude 43°10', is kept in the Collection of Historical Scientific Instruments in Harvard, bought in Paris in 1929.

The Hartmann refractive bowl I studied was originally provided with a style, tilted in the same way as the polar axis is tilted in the place where it's used.
Considering the bowl without water, at civil hour, all the shade of the style indicates the hour overlapping or interposing precisely at the hour lines, getting in this way an immediate and good readability of the dial.
Filling the bowl with water, only the end of the shade indicates exactly the hour, because near the meridian the shade doesn't undergo the 'onion deformation' of the hour lines the artisan drew on the dial in order to make it work correctly. The choice made by Hartmann is a good compromise around midday, between 10 AM and 2 PM, when the imperfection is not evident.

The bowl of Madrid has a star engraved on the superior part, made of a small circle with 6 rays, to indicate the Polar direction, i.e. the North. In the sundial there is a lot of evident approximation in the sketch of the lines, especially the seasonal ones rippling, not symmetric and discontinuous in points where pieces with different curvature are bad linked (between IX

and X in the morning and I and III in the afternoon), moreover in two points there is no link (at hour III for the curves of the Water Carrier and the two Fish). The irregular shape of the free spaces between the curves underlines the uncertainty of the draw.
The inscription on the border ends with the signs YH, that looks like the two letters of the following word HYDRAULICUM mirror-written (as the prints engravers were used to do).
The handwriting at the end of the bowl is older; instead of the modern number *2* is still used the one with *Z* shape. The interior of the dial has instead better well-finished inscriptions: maybe two different hands worked at the bowl, one for the rougher and in old style inscription, the other one for the graduation.
Traces of the original gilding can be still noticed in the interior part of the hemisphere.

If we want to believe that the Hartmann refractive sundial really copies the miracle of Isaia, that miracle has to be reproduced after midday because in the morning the water poured in the bowl makes the shade go towards the central hours and not come back; the propitious hours are the ones in the early afternoon: whenever the evening comes, the refraction changes the indications of the shade more of the 10° required in the Bible; also the date has to be chosen between late spring and beginning of summer.

It has been a pleasure to discover that the gnomon of the bowl, built with a spoke of my father's old motorbike was auctioned at high price and that now it is shown at the museum of Madrid!
Unluckily the Spanish bent it too much, maybe thinking that the bowl has to be filled only partially, as we can argue from the rough animation on the museum web site: that prevents the right work of the refractive sundial and makes my repair useless.
The researchers of the museum in Madrid also changed the origin of the two twin Hartmann bowl saying that they could have been purchased by nobles from Toledo and Lombardia (who were in Germany with Charles V), in order to make a present to some ecclesiastics in Rome (M. VILLAVERDE APARICIO, *Ciencia, religiòn y astrologia: Georg Hartmann en el Museo Nacional de Cienca y Tecnologia*, 'Actes de la VIII trobada d'Història de la Ciencia i de la Tecnica', Barcelona 2006, pp. 303-305).

Has the refraction in the fountain of Urbino disappeared?

When speaking of refractive sundials it is always mentioned the famous treatise *De gli Horologi Solari* by Muzio Oddi and the fountain that lies in the roof garden of *Palazzo Ducale di Urbino*.
The researchers who speak about this fountain (E. GAMBA, *La meridiana a rifrazione nella fontana del giardino pensile*, in *Il Palazzo di Federico da Montefeltro. Restauri e ricerche*, Urbino 1985, pp. 553-556; R. PANICALI, *Orologi e orologiai del Rinascimento italiano: la scuola Urbinate,* Urbino 1988, pp. 122-129; F. CAMEROTA, *Two new attributions: a refractive dial of Guidobaldo del Monte and the "Roverino compass" of Fabrizio Mordente*, 'Nuncius', A. 18, vol.1 (2003), pp. 25-37) say, backing up the known documents, that the dial described at the beginning of '600 is the one we can observe in Palazzo Ducale di Urbino. But is this dial the same described by Oddi? Without doubts the dial of Urbino is built in a garden basin as the one Oddi saw about 4 centuries ago!
A careful inspection shows that the marmoreal fountain with the shape of a basin (semi-elliptical according to Camerota, even if it's not a regular geometrical shape) could not be the one described by Oddi: the dial lines are clearly the ones of a 'dry' bowl indicating italic hours and not the ones of a refractive sundial.

In refractive bowls the rim doesn't have any marks because it's never reached by the shadow of the gnomon, while the useful part of the dial, together with hour and month lines, is crescent shaped due to the refraction; instead in 'dry' sundials the shape is a band that widens as a 'butterfly' if the container is flat and above all, the XXIV hour of the day (sunset), coincides with the rim of the bowl, as in the case of the fountain of Urbino.
The remarks and reconstructions published by Gamba and Panicali seem to be right even if the two authors don't agree on the starting point of the hour lines: for the first the lines start at 9th italic hour, for the second at 11th italic hour.
It's instead absolutly unusual the matching (presented by Panicali) on the equinoctial of the French hours; that could induce to think that the lines carved in the basin indicate the time both in the italic system and in the French one. But in the last hour system these lines follow a completely different behaviour.
Also the reconstruction published by Camerota is well founded; from the picture he attaches, it can be seen that the hour lines start from 10, even if the author claims they begin from 9. This inconsistency could be explained observing that in the longest day the sun rises in Urbino at the italic 8:33.
Naturally the basin worked as a sundial through a gnomon fixed in the centre that reached with its height the rim; unluckily now there is only a hole topped with a modern marmoreal plug, whereas originally there was probably a statuette or another pinnacle that supported the jet of the fountain.
Referring to a sundial for italic hours, only the end of the shade of the style indicated the time; any tilt of the style (that usually is in perpendicular position) is useless.
From 17 until nearly 22 italic hours, the sundial of the fountain differs slightly from a sundial realized on a flat surface. In a horizontal sundial before 17 and after 22 italic hours the lines go to infinity, instead in the basin of the fountain, as well as in all sundials built in a cavity, the turning up boundaries let these limits exceed. These limits were really a pane in the italic compute of hours because the main hour of the day was the twenty-fourth when the computation of hours restarted and Ave Maria could ring.
We might say that the sundial of Palazzo Ducale di Urbino is very similar to the diptych sundials of Nuremberg realized in slightly deep cavities.

A careful study of the images and information provided by Roberto Mantovani, curator of the physics laboratory of the University of Urbino, let me conclude that the maker of the sundial of the roof garden built the sketch using only three points for every hour, two in the extremities, where the shade of style arrives during solstices, the third in the middle where the shade arrives during equinoxes. These points were marked in the marble drilling small holes still well evident.
Then the hour lines were easily obtained connecting the extremities with straight segments or at most, with simple arches on the boundary; moreover the equinoctial line was obtained connecting the central points.
The uncertainties of the original project are highlighted by the fact that these points are not aligned and from the fact that in the final draw the author tried to average out the different gaps.
The procedure looks like the one described in the manuals of that time and is correct for a flat surface. But Urbino's basin is not flat and the mistakes made are hard to control, mainly in the morning and in the evening, when the shade falls in the most curved part of the basin: the lines had to be built with a big number of points. So the 'practical' artisan didn't lose himself in virtuosity (useless for such a dial of small dimensions); the reading of time is rough: there are no marks for time fractions, the identification of the end of the shade is uncertain, the atmospheric refraction in the first and last hours of the day and the shape of the instrument

are not regular. Moreover there are mistakes in the orientation of the instrument, in its horizontal position, in the perpendicularity of the gnomon and in the ground settling.
At this point I would like to end with the words of Fantoni: ‘Il tracciamento dei diagrammi orari sulle altre superfici curve si presenta decisamente più complesso. Abili matematici e geometri hanno elaborato, specie negli ultimi secoli, vari metodi analitici o grafici per disegnare questi tipi di strumenti (…) Peraltro l’astrusità delle soluzioni analitiche, dense di ostiche formule, e l’imprecisione delle complesse soluzioni geometriche le mettono tutte, a mio parere, al di fuori del campo della pratica. Con molta maggiore facilità il tracciamento di orologi solari su superfici qualsiasi (…) si può fare usando appositi attrezzi che hanno avuto larga diffusione e impiego nel passato (…) L’uso di questi strumenti costruttivi porta a soluzioni empiriche di dubbia precisione, barattando esattezza con facilità di esecuzione; peraltro esso rappresenta a mio giudizio l’unico sistema pratico per tracciare quadranti solari su superfici di qualsiasi natura geometrica” (G. FANTONI, *Orologi Solari. Trattato completo di gnomonica*, Roma 1988, p. 330)[1].

The height of the lost style can be evaluated computing the distance *D* from the centre of the basin to the crossing point between the meridian line, the equinoctial one and the line of 18, (where the shade of the gnomon arrives at midday of equinoctials). By knowing that in such a time the distance of the sun from the celestial Pole is of 90° and that it is high on the horizon of an angle equal to the latitude of the place (Urbino: 43°43’27’’ Lat. N), follows that $H=D\cdot\tan\cdot Lat$. where *H* is the height of the vertical gnomon; that means $H=1{,}045\cdot D$ so the original vertical style was about as long as the distance between the centre of the basin and the crossing of the previous lines.
In order to obtain a shadow that arrives at the rim of the basin at sunset, the height of the style has to be exactly equal to the depth of the basin in the point where the style was fixed.
All the previous argument has been made without using refraction, so the fact that it works in Urbino’s basin proves that the lines in that basin are not related to an instrument that works with water.

At the actual state of knowledge, it is possible to assume that the two Hartmann’s hemispheric twin bowl of 1547-1548 belong to the family of refractive sundials, the bowl kept in the Museo di Storia della Scienza of Firenze, the one of Christoph Schissler dated 1578 and kept by the American Philosophical Society of Philadelphia, three conical chalice dials signed Markus Purmann, the first dated 1590 at the Germanisches Nationalmuseum of Nürnberg, the second dated 1599 at the Museum of History of Science of Oxford and the third dated 1608 belonging to Phillips Auction, published in J.F. Mills, *Encyclopedia of Antique Scientific Instruments*, London 1983, table VII.

The so far known refractive sundials are directional sundials: the direction of sun is useful to indicate the time, the height of the sun is used to indicate the entrance into the in signs of the zodiac and so it works as a calendar.
Completely in the wrong direction is Dupré, who as well as speaking of Urbino’s basin as a version of the refractive horizontal sundial, also states ‘The bowl sundials are a subset of

[1] «The draw of time diagrams on curved surface is definitely complicated. Expert mathematicians and geometers elaborated, especially in the last centuries, different analytical or graphical methods to build these kinds of instruments (...) Moreover the hard analytical solutions and the lack of accuracy in the complicated geometrical solutions make them, in my opinion, unusable. The draw of sundial (…) can be done simply with suitable tools that had large diffusion and use in the past (...) These instruments lead to empiric solutions of doubtful precision, but make a tradeoff between the exactness of the draw and the easiness in the construction; moreover, in my opinion this is the only practical way to trace sundial on any surface.»

altitude sundials where the time is determined by the height of sun in the horizon' (S. DUPRÉ, *The dioptrics of refractive dials in sixteenth century*, 'Nuncius', A. 18, vol. 1 (2003), p. 65).
It's not better the *Catalogue of Sun-dials, Nocturnals and Related Instruments*, published in 2007 from IMSS of Firenze and edited by A. J. Turner, that immediately at the first page (p.8) classifies in a table all the spheric or conic *Schaphe* among 'altitude dials'.
So in the chapter about altitude sundials (pp 64-67) there is the refractive bowl attributed to Barocci together with the multiple bowl of Bonsignori, made by 4 sundials at italic time drawn in small bowl (pp. 66-69). The same identical dials, but arranged in a polyhedron by the Florentine cosmographer, are classified among the directional dials.

Where does the bowl of Firenze come from?

Following the precious information of Muzio Oddi in his treatise *De gli Horologi Solari*, we know that in 1572 the mathematician and scientist Guidobaldo del Monte had refractive sundial in a brass hemispheric manufactured by Simone Barroci (very good craftsman of scientific instruments) from Urbino.
After several years Oddi became Guidobaldo's scholar and had this clock in his hands for a lot of time while the duke Francesco Maria II della Rovere used it as a model for another similar one, after 1587, in the Urbino's fountain.
Another scholar of Guidobaldo, Bernardino Baldi, dedicated an inscription to the bowl sundial.
In a letter dated 1634 Oddi seemed interested to buy the refractive sundial that, in his opinion, was owned by the heirs of Guidobaldo (CAMEROTA, *Two new attributions*, cit., p. 31).
So the bowl, kept in the wardrobe of Palazzo Vecchio in Firenze since 1572 and now kept in the museum of historical science of the city, clearly can't be the one described by Oddi and Baldi, as instead states the recent attribution (CAMEROTA, *Two new attributions*, cit., p. 25) also confirmed in the catalogues and in the publications of the museum.

In 'Nuncius' (p. 30) Camerota (in order to attribute the refractive bowl kept in Firenze to Simone Barocci) says that the tilt of the style and the equinoctial line equal to 32°, corresponding to the value of Urbino latitude (43°30') refracted by the bowl. But when the light beams pass from air to water, 32° is obtained as the refraction of 44°56' and not of 43°30'. Moreover in the maps of Italy printed in the second half of 1500, 45° matches usually with the latitude of Venezia and not with the one of Urbino or Firenze.
The heights of the Sun on meridian during solstices, indicated in the draw published by Camerota, are obtained simply following the school manuals, adding and subtracting the tilt of 23°30' of the ecliptic at the latitude of 43°30' (instead of using refraction and calculating the values starting from measures noted on the interior part of the vase).
Assuming that modern measures have been made with the right precision and ignoring the uncertainty in the manufacturing of the sundial and its deformations caused by time, then the angles of 16° and 45° indicated for the refracted solstices induce to think that the bowl was realized respectively for a latitude of 45° and 47° and so one can deduce that the refractive sundial of Firenze wasn't built to be used neither in Firenze nor in Urbino.

Again according to Camerota (p. 31) the Florentine bowl comes from Urbino because of the decoration in the central part of its cover. In his opinion this decoration is a gland surrounded by oak leaves, heraldic symbol of the family Della Rovere.
The presumed evidence is very weak: the decoration of the cover couldn't be considered an unmistakable symbol, but rather it looks like a very common decorative element used in pictures, 'stucchi' in churches and palaces or in wood intaglios.

Anyway, restricting our analysis at the scientific instruments of Renaissance and more in particular at the ones shown in the museum of Firenze, it's possible to find similar floreal motifs in astrolabes by Regiomontano, Hartmann, Schlisser, Mercatore, in the dial by Schissler and also in the mathematical instruments by Lusverg or even in the decoration graved on Galileo's 'Giovilabio'. Also the *Astronomicum Caesareum* of Pietro Appiano shows different decorations of that kind in the middle of the wheel charts.

When the catalogue of the florentine museum still classified the refractive bowl as a simple 'bowl or «scaphea» sundial of ancient origin' (M. MINIATI, *Museo di Storia della Scienza. Catalogo*, Firenze 1991, p. 12) I guessed, only observing the small picture published at that time, that it was a refractive dial, the only similar to the Hartmann sundial I had in my hands (as I wrote in the article on 'Gnomonica' (p. 16)). Also without analyzing the details (as Camerota made), the refractive bowls are immediately recognizable by the position of lines respect to the rim of the recipient and respect to the tip of the gnomon.

The bowl of Firenze is a hemispheric brass container supported by a pedestal and with a cover useful to avoid the pouring and the evaporation of water; near the rim, on the exterior side, is fixed the bearing of a compass.
A strong sharpened style, tilted of 32° respect to horizontal, reaches with its tip the centre of the bowl, at the level of the upper rim. Inside the bowl thin curves are carved in the metal, with some uncertainty, folded up in order to take in to account the refractive effects: the meridian line, the equinoctial line and 15 time lines starting from the italic 9. Instead there isn't any trace of the two solstitial lines.
All the marks on the sundial are framed in the inferior section, bounded on the top from a horizontal ring since the light beams, passing from air to water, have a limit angle of 48°36' that the shade of the gnomon can never exceed in order to be projected on the above area opportunely kept clear by the artisan. When the bowl is filled up with water until the rim, this circle is lapped by the shade at sunshine and at sunset (corresponding at 24 in the italic hour system).
The marks on the bowl are evidently very simple and reduced to the essential, there is no comparison with the Hartmann bowls and even less with the precious Schiller chalices, provided with a double line grid that let them work with or without water.

The bowl of Firenze is an italic hour dial that indicates the time using only the shade of the tip of the gnomon, making useless any tilt of the style. The first impression is then that the tilt of style is a mistake of the artisan, maybe he planned to add also a diagram with civil hours, as was usual at that time. Another hypothesis is that the craftsman took another bowl with civil hours as a model.
Anyway, as I said before, also counting the civil hours from midnight, the use of a style parallel to the polar axis achieves the desired effect only using a bowl without water: its whole shade would indicate the time. When, on the contrary, the bowl is filled with water the tip of the shade indicates accurately the time and the choice of a tilted gnomon is a good compromise only for the time around midday.
The solution adopted in the Florentine dial, i.e. the tilt of the celestial axis refracted (32°), is very peculiar and, without doubts, was adopted in an empiric way with the aim of improving the results; but the effort was useless because the sundial is not a civil hour sundial but only an italic hour sundial.

The artisan of the refractive bowl of Firenze didn't take the Hartmann bowl as a model: the tilt of the gnomon, the draw of lines and the position of the compass show an autonomous project with respect to the Teutonic's dials.

Moreover the Hartmann bowls don't have any decorative elements but are very precise in the scientific manufacturing and in the marks inscripted; on the contrary the florentine dial is well decorated but has not many marks, probably the craftsman didn't have much scientific knowledge or found technical difficulties in progress.
Since the bowl (without date and signature) belonged to the Medici collection from Firenze already before 1570-72, it could be possibly dated before the ones of the famous craftsman from Nürnberg.

It's possible that Ettore Ausonio (the most proficient Italian scientist in the field of refraction in the middle of 1500, mathematician and craftsman of optical instruments in Venezia) was involved in the execution of the refractive bowl of the grand duke of Toscana; without any doubts he was able to build it, as it's clear from the letter he sent in 1562 to the duke Emanuele Filiberto of Savoia in which Ausonio wrote: 'Faremo (...) li horologij delle refrattioni (we will make the refractive sundials)' (DUPRÉ, *The dioptrics*, cit., pp 57-58).
Among the handwritten notes of Ausonio (kept in the Biblioteca Ambrosiana) there is a table with the values of angle of incidence and refraction; this table is useful to build a refractive sundial at the latitude of 45° of his town. For a value of the refraction angle close to the limit angle, the calculation of Ausonio is overestimated of more than one degree (DUPRÉ, *The dioptrics*, cit., pp 61-62), this mistake could justify the anomalous behaviour (47° for the latitude) of the bowl at midday of the winter solstice.

1. Hartmann watch seen without water.
2. Soon after, when the bowl is filled with water, the shadow retrocedes of about ten degrees: Isaia's miracle can occur!
3. Leaflet for Sotheby's auction of April 1999 with the refractive bowl.
   Detail of the fountain of Palazzo Ducale in Urbino, where the eastern rim with the line of the 23 italic hours is clearly visible (photo R. Mantovani).
4. Detail of the western portion of the fountain of Palazzo Ducale where it is possible to see the holes used by the craftsman to trace the hour and the equinoctial lines.
   Of the top of it is possible to read the indication of the 16 (photo R. Mantovani).
5. Hartman watch after the first cleaning.
6. Magnified northern portion.
7. Hartmann watch with gnomon, compass and water.
8. Southern portion.
9. Magnified southern portion.
10. Northern portion.
11. Magnified northern portion.
12. Western portion.
13. Eastern portion.

The first article written by Lino Colombo and published in "Gnomonica" (n. 1, 1998) follows.

The sundial of Acaz

A refractive sundial of George Hartmann dated 1547

The hemispheric brass object (diameter 153 mm, height 81 mm), dirty and unknown, was discovered by an antique dealer in Busto Arsizio in mid-April 1998. It's a bowl sundial, or according to the Greek denomination, a *skaphe* (cavity), thus one of the most ancient shape of sundial, so far known, marked in the internal surface of a bowl; there are, on the other hand, a lot of examples of marble sundials dating back to the roman period. After many centuries, around 1500, the construction of sundials started again. In general of small size, portable, realized in metal, our bowl constitutes a remarkable example of such bowls (R.R.J. ROHR, *Les Cadrans Solaires. Historie, Théorie, Pratique*, Strasbourg, 1986, pp. 17-19, 21, 156; G. FANTONI, *Orologi Solari. Trattato completo di gnomonica*, Roma 1988, pp. 328-331).

In the hemisphere discovered, there are 15 hour-lines marked on the bottom of the bowl; these lines are numbered from V in the morning to VII in the evening and are intersected by 7 calendarial lines, made by conic curves denoting the entrance of the sun into the zodiac signs (and are recognized from the corresponding signs). The day hours are roughly marked by the whole shade of the style, whereas the date is readable from the end point of the style itself. As well as nowadays, the hours are counted starting from midnight, according to the German hour system used also in Italy since the end of 17th century.

The shape of the discovered sundial has a lot of resemblances with the ancient bowls but it works in a peculiar way: in order to use the instrument in the right way we have to fill it with water until the rim (0.8 litres). In fact, an inscription says: HORE A MERIDIE ET SIGNA SOLIS COGNOSCVNTVR EX REFRACTIONE (hours and signs can be read through the refraction of light in the water inside the bowl). Moreover, without filling the bowl with water, we couldn't have, in some part of the year, any projection of the shade of the gnomon on the dial. In fact the water bends the light beams of some degrees and send them on the bottom of the bowl among the lines marked with precision by the maker. These lines are deformed with respect to the ones marked on the common bowl sundials, since refraction increases when the sun goes to the horizon.

All the signs are contained in a framed basin of 50° degrees, the missing 40° degrees of the hemisphere being empty because the light beams passing from air to water have a limit angle of 48.6° that the shade of the gnomon can't never exceed, in order to project on the superior band.

The interior of the bowl is divided by the meridian line in two equal parts, graduated in the northern part from 10° to 90° degrees and with the inscription: GRADVS ASCENSIONVM SOLIS; so it has the function to measure the height of the sun in the sky, or, more precisely, the zenithal distance of the star.

The superior rim of the bowl has a thickness of 3 mm and it's decorated inside, for all the length of the circumference, by the inscription: HYDRAVLICUM QUOD MIRABILI ARTIFICIO * IMITATVR * HOROLOGIVM ACHAS IN QUO ESAIAS VMBRAM SOLIS RETRORSVM DVXIT DECEM GRADIBVS· QVARTO REGVM· 20· CA· ESAIE· 38· CA: PARA; LI: 2: CA: 32 YH. So the instrument is called 'hydraulic' and imitates the sundial of Acaz, king of Giuda (736-721 B.C.) with an 'admirable artifice'. We can see in fact that the artisan refers to the Bible (*Fourth book of Kings*, chapter 20; *Isaias*, chapter 38; *Second book of Paralipomenon*, chapter 32) and claims that the sundial works according to the miracle of God that, invoked by the prophet Isaiah, made the shade of the Acaz sundial come back of 10°, deviating the sun beams.

It's clear that the craftsman of the sundial perfectly knew the effects of refraction, even if in an empirical way; the law that explains the refraction in a precise way was found by Snellius

(Willebrord Snel van Rojen) in 1621 and was formulated definitively by Cartesius (René Descartes) in the following decade:

$$\sin i = n\cdot\sin r$$

where i is the angle of incidence (made by the perpendicular to the surface of interface between two different mediums and the incident ray), r is the refraction angle (made by the perpendicular and the refracted ray), n is the relative refraction index of the second medium with respect to the first one, in our case water respect to air (equal to 1.333).

In order to make the sundial work, it is necessary to point its style in the direction of the North Pole. The style is now missing, but it was set in the inner side of the bowl making an angle of 48° with the bottom. Its tip was exactly in the centre of the sphere and so it made an angle, with respect to the horizontal plane, equal to the latitude for which the bowl was calibrated; this latitude is indicated in the inscription on a small semicircle at the base of the gnomon: POLVS GRA· 41· Mi· 41·, corresponding to the city of Rome where the height of the pole over the horizontal is circa 41°41'. The right latitude of Rome is 41°54', but in 1500 its value was fully undervalued, as all the maps of that time show (R. ALMAGIÀ, *Monumenta Italiae Cartographica*, Firenze 1929, p. 73); for example the map of Italy published in 1561 by Girolamo Ruscelli sets Rome at the same latitude indicated in the sundial (G. RUSCELLI, *La Geografia di Claudio Tolomeo alessandrino*, Venezia 1561).

The right functioning of the instrument could be obtained through a small compass, also missing, to be fixed under the bottom of the bowl. Instead of the compass now there is a hole with a diameter of 18 mm, with a corona carved around, where we can read the 4 cardinal points: SEP[tentrio], ME[ridies], OR[iens], OC[cidens].

On the bottom part of the gnomon the date and the signature of the artisan are written: RADIORVM SOLIS IN AQVA GEORGIVS HARTMAN NORENBERGE ·F· 1547, that is: in Nürnberg, 1547, Georg Hartmann studied sun rays in water. Georg Hartmann (1489-1564), Vicar of the church of St. Sebaldus in Nürnberg, was a renaissance pioneer in building scientific instruments. In his studio many astrolabes, dials, sundials, globes and armillary spheres were produced; today we still have a hundred of this instruments (A. TURNER, *Early scientific Instruments Europe 1400-1800*, London 1987, pp. 39-47). Hartmann was also a pioneer in the study of the declination and magnetic tilt of compasses: in 1510 he measured the magnetic declination in Rome, in 1544 he was the first to notice that the magnetic needle 'was tilted towards the ground' (R. PITONI, *Storia della Fisica*, Torino 1919, p. 100).

The Museo di Storia della Scienza of Firenze possesses a bowl sundial of the same period and with the same manufacture as the one just examined; the florentine bowl presents a cover that probably had the function to prevent the pouring and the evaporation of the water inside. The same museum has also a gilded copper astrolabe produced in Nürnberg by Georg Hartmann in 1545 (AA.Vv., *Museo di Storia della Scienza Firenze. Catalogo*, Firenze 1991, pp. 12-13, 30).

At the end of April we restored our discovered sundial, removing the dirty, reconstructing the style in the right dimension and putting a modern compass in the hole. By filling the bowl with water it worked again indicating the right solar local time. In order to verify that the bowl is perfectly horizontal one as to check that the water surface is aligned with the lines indicated on the rim; the water lifts up the image on the bottom, so that the bowl looks less curved and the marks on the bottom are more easily readable.

Our deductions, obtained interpreting the inscriptions and studying the lines marked on the bowl, find a confirm in the treatise *De gli Horologi solari* published in 1683 by the architect and mathematician Muzio Oddi from Urbino (1569-1639); in fact the author, in the chapter dedicated to refractive clocks says: «Tra quante cose belle, & ammirabili, che in proposito d'horologi da Sole sono state ritrovate infino al giorno d'hoggi, nissuna è che per mio credere pareggi quella di farli nel concavo di un vaso, con si fatto artifitio, che l'ombra non mostri l'hore giuste, se non quando è tutto ripieno d'acqua, non potendosi non senza meraviglia

vedere, che col fare i Raggi Rifranti, storcere l'ombra dello Gnomone, la drizzano in parte, che ne faccia conoscere il vero»[2].
Oddi listed also the few examples of this type of clocks he knew: «Chi di così curiosa cosa ne sia stato l'autore, non saprei darne certa notitia, non sapendo che nessuno de gl'Antichi n'abbia lasciato memoria alcuna: ben sò de moderni, che l'anno 1572. L'Illustrissimo Signor Guidobaldo de Marchesi del Monte ne fece fare uno da Simone Baroccio, eccellente artefice, in una mezza sfera d'Ottone, & hollo havuto nelle mani molto tempo, il quale servì poi come modello d'uno, che d'ordine del Duca Francesco Maria Secondo, ne fù fabbricato entro la tazza della fonte, che è nel Giardino pensile del suo Magnificentissimo Palazzo d'Urbino; come si vede fino al giorno d'hoggi: e circa a i medesimi tempi Gio: Battista Benedetti publicò la sua Gnomonica, nella quale fece mentione con un particolare Capitolo di questo istesso Horologio: & un giorno parlandone io col Padre Christophoro Clavio in Roma, mi disse, che Giovanni da Monteregio n'havea fatto uno ancor lui, per un Prencipe d'Alemagna. Si conservano ancora presso di me alcuni fogli disegnati dal Commandino, che, per quanto hò potuto conietturare, giua cercando la ragione della varietà de gl'angoli delle refrattioni, non retirandosi uniformemente l'ombre fatte dal Gnomone, quando il Sole è vicino all'Orizonte, da quando è alto da terra, benche habbia trascorso intervalli uguali, forse per comporne le tavole à questo effetto, non essendo le medesime, che quelle d'Alazeno, e di Vittellione. Nè il Benedetti, nè il Signor Guidobaldo le fecero; ma solo acennarono il come si haverebbe à fare per comporle, e prò la fabrica di questi Horologi, fino adesso, si riduce ad una mera pratica»[3].
This confirms that the sketch of the refractive dials was done practically, and not theoretically; Oddi himself described a way to realize the sundials using a lamp to simulate the different positions of the sun in the sky.
We can conclude that bowl sundials are very rare. They were produced in Germany for a short period between 1550 and 1600, so that only few models can be found in museums; in particular the sundial nowadays discovered is not only a peculiar bowl refractive sundial, but it's probably the most ancient instrument of this type (A.A. MILLS, *Chalice dials*, 'Bulletin of the British Sundial Society' 96.1, October 1995, pp. 19-26). Thanks to the precious cooperation with two experts of gnomonic, such as Alberto Cintio and Nicola Severino, we have come to know that the Spanish museum of Santa Cruz in Toledo has got a sundial perfectly identical to the one we have studied (A.A. MILLS, *Chalice dials*, 'Bulletin of the British Sundial Society' 96.1, February 1996, p. 35). This isn't a surprising fact because the author was a precursor for the 'mass production' of scientific instruments, starting from a single model.

Dairago, May 1998

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[2] «Among the fine and admirable things discovered sofar, in my opinion, nothing is better than the idea of building them in a bowl, so that we can read the exact hour only when it is filled with water: we are surprised observing that light beams, refracted by water, twist and partially straighten the shade of the gnomon and we can view the actual measurement».

[3] «I can't tell who the artisan of such a curious instrument was, since I don't have knowledge of any historical information. I only have some about the present times: in 1572 the distinguished Guidobaldo de Marchesi del Monte ordered to Simone Barocci, skilful artisan, a sundial in a half brass sphere and I had it in my hands for a long time. This sundial was used as a model for another one ordered by the duke Francesco Maria Secondo and realized in the bowl of the roof garden of the fountain in the magnificent Palazzo di Urbino, as we can see nowadays. In the same time Giovanni Battista Benedetti published the *Gnomonica*, where he mentions this dial in a specific chapter. Talking with Padre Cristoforo Clavio in Rome, I came to know that Giovanni da Monteregio had built a sundial for a prince of Germany. I have some drawn papers by Commandino in which, I guess, he was trying to discover the variety of refraction angles and to understand why the shade formed by the gnomon does not change uniformly when the sun is close to the horizon and or it's high above the ground, even though we are considering equal intervals; maybe he had the aim to fill some tables different from the ones of Alhazen and Vitellione. Neither Benetti, nor Guidobaldo made some kind of tables, they only sketched how those could be done. Anyway the sundial manufacture is nowadays only a practical art».

On May 29th the assessorship for culture of Dairago (Milan, Italy), where Lino Colombo lives, dedicated an event (entitled 'UNA MERIDIANA A TAZZA D'ACQUA the miracle of the prophet Isaiah artfully reproduced, by Lino Colombo'*) to show and explain the refractive sundial.*
The sundial was shown to an interested audience: everybody was surprised by its functioning reproduced by means of a lamp (projector).
On that occasion the mayor of the town accepted the proposal to make a stone magnified copy of the sundial that could be a piece of local furniture, useful to remember the sundial and its short stay in our town.

Translated by Anna Zanzottera