MONITORING COASTAL AREAS: A BRIEF HISTORY OF MEASURING INSTRUMENTS FOR SOLAR RADIATION

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Abstract – The beginning of the development of instruments for the measurement of solar radiation is quite recent even though this quantity is the main engine of environmental physics and marine and terrestrial biology and their primary connection element as it was highlighted by environmental physics studies since second half of the 19th century. Although already in the classical era there were some mentions to the concept of solar radiation, in terms of heat and light, discussions on the role of the Sun remained on a philosophical level until the scientific revolution when the first studies were made, in the astronomical field, about solar radiation. Only in the first half of the 19th century the first specific instruments were made for measuring solar radiation for meteorological purposes such as the Pouillet pyrheliometer.

The birth of the *Organization Météorologique Internationale*, OMI, (1879) started the process that will lead to the standardization of instruments and observation methodologies for solarimetry. In 1896 OMI established the *Solar Radiation Commission*. In 1905, Third Conference of Directors of National Meteorological Services decided to take the Ångström pyrheliometer as a standard instrument. In the following decades, other types of radiometers were development to measure the other components of solar radiation (such as the Robitzsch pyranograph in 1932) from which began the realization of instruments whose signal could be recorded analogically on the acquisition data system. Other pyranometers were realized to measure the intensity of the radiation using the Moll-Gorczynki thermopile; other versions were built using a photocell as a sensitive element.

In the last decades of the 20th century, digital recording instruments for radiometry were also realized. Furthermore, instruments have been developed that drastically reduce maintenance operations, an essential aspect for quantities measures, such as sunshine duration and diffuse radiation, performed in remote and difficult to reach sites. In the 2000s, for studies concerning physical and biological marine-oceanic quantities, apparatuses were developed for measuring solar radiation in the water column in the global blue, green and red ranges.

Introduction

Environmental physics studies of the last 150 years have shown that solar energy drives all the phenomena that occur in the atmosphere, in the oceans and on earth. In the marine and coastal environment, radiation provides the surface layers of the oceans and seas with the energy necessary for water to pass from the liquid to the vapor state, triggering the hydrological cycle. Solar radiation influences, among other phenomena, hydrodynamisms such as wave motion and sea currents and the qualitative and quantitative development of marine ecosystems. In reference to marine biology, while solar radiation is relatively little affected by the thickness of the atmosphere, it is strongly and selectively influenced by the thickness of the water. In

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other words, the different frequencies that make up the visible radiation are attenuated differently from the water thickness.

In recent decades, the measure of solar radiation, especially in the UV range, has assumed importance in coastal marine areas also for the purpose of health safety of inhabitants of these areas. Various studies have showed that the greater exposure to radiation causes the onset of dermatological diseases to increase both for outdoor workers (fishermen, construction workers, lifeguards, sailors, etc.) and for beach tourists.

The Origins

The first references to a concept of solar radiation, even if in terms of heat and light, are due to Aristotle who in *Περὶ οὐρανοῦ* (On the Heavens) states that the heat and light of the stars, including the Sun, are the result of their movement that creating friction causes the ignition of the underlying air. According to Aristotle, the heat generated by the Sun gives rise on the earth's surface to a dry and a wet and cold hot exhalation that arise from the Earth and contribute to various meteorological phenomena. In classical era also Pliny the Elder wrote about the important the role of the Sun on terrestrial activities in his work *Naturalis Historia*, where he asserted that the effects of the Sun are very strong on Earth (*de cujus sideris effectas amplissimi in terra sentiuntur*).

Discussions on the role of the Sun remained purely philosophical until the scientific revolution (16th-17th century) when the first studies on solar radiation were carried out. However, for almost three centuries these studies were an astronomers' exclusive research field. Although solar radiation is the main engine of environmental physics of terrestrial and marine biology, their primary connecting element, the beginning of the study for its measurement and construction of instruments is quite recent.

It was probably H. B. de Sassure (1767 and following years) the first to contrive an instrument for measuring solar radiation. The instrument, *heliothermometer*, consisted of a mercury thermometer with blackened bulb protected by a transparent thin glass bubble to prevent air currents, or other disturbances, from influencing the measurement [11]. The thermometer, in the first version with a Réamur scale, was placed in a wooden box covered with blackened cork and covered with three spaced glass plates [1] [5]. Around 1774 it seems that de Saussure used *heliothermometer* to directly compare the measurement of “solar heat” intensity at the top and bottom of a mountain [18]. Thanks to this instrument, de Saussure was the first to demonstrate the increase in solar radiation with altitude [5].

The development of the instruments

Only at the beginning of the 19th century, instruments for measuring solar radiation, for meteorological purposes, were made such as J. Herschel's actinometer (radiation gauge, from the Greek *aktis* radius) (1825) [4] and the *caloric collector* (later referred to as a *lucimeter*[1], or *totalizer actinometer* or *distillation actinometer*) by A. Bellani (1836) [9], [27].

[1] It was also called *lucimeter* since it was sensitive only to the visible range of solar radiation [28].

The original version[2], of Bellani instrument (figure 1) consisted of a graduated glass tube (T) with the lower end closed; the upper part, curved in the last section, ended in a glass sphere (A) containing easily evaporable liquid (ether or alcohol) inside which the vacuum was made. To measure the average intensity of solar radiation in a certain period, the sphere was wrapped with a black cloth. When the temperature of sphere was higher than that of the tube, the liquid evaporated and condensed collecting at the bottom of it. The level reached by the liquid in the tube allowed to find the quantity of light energy (in the visible field) received in a certain interval of time. [6], [27].

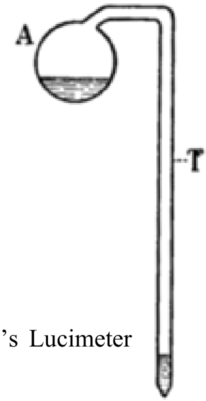

Figure 1 - Bellani's Lucimeter (1836). From [27].

These instruments were followed in 1837 by a specific for measuring the intensity of solar radiation, the Pouillet pyrheliometer, based on a water calorimeter (figure 2) [19]. Pouillet managed to estimate the solar constant with the measurements made with this instrument, which detected only the direct component of the radiation. [8].

Figure 2 - Pouillet's pyrheliometer (1837). A: container (calorimeter), with blackened receiver, made with a silver foil and filled with water. T: thermometer whose bulb enters the container to measure the water temperature. C-D alignment check system to orient the instrument towards the Sun. Disk in C to check the orthogonality of the sunrays with respect to the blackened surface of the calorimeter. From [9]

From the mid-nineteenth century, the first instruments for measuring sunshine duration were made that is *the time in which, during the day, the Sun manifests itself in a cloudless sky* [3]. In 1853 J. F. Campbell proposed a sunshine recorder which consisted of a

[2] In the modified (more common) version, the graduated tube (straight) had the lower end closed, while the upper open and sharpened one penetrated into a spherical glass ampoule (containing liquid evaporable in an air-free environment) colored blue. The ampoule was inside another transparent ampoule in which the vacuum had been practiced. [28]. Each lucimeter had its own sensitivity which decreased when the blue sphere was emptied, according to a law that varied from one specimen to another. To overcome this drawback, a correction table was used to bring the measurements back to those that would were carried out with an ideal instrument in standard conditions [9].

[3] The WMO current definition states: sunshine duration during a given period is defined as the sum of the time for which the direct solar irradiance exceeds 120 W m^{-2} [32].

glass sphere placed in a wooden container from which it partially protruded (Figure 3a). The sphere acted as a converging lens of the sunrays which focused on the container cavity and burned the walls at different heights, day by day, and at different times of the year. The length of the burn trace indicated, roughly, the duration of presence of the Sun. The tracks produced daily tended to partially overlap, therefore their reading was not easy. The direct burning of the wood of the container made it usable only for six months and therefore it was necessary to replace it twice a year.

Figure 3.A - Campbell's sunshine recorder: the spherical lens is inside the container; on the internal wall of the latter are visible burning traces produced by solar radiation. From [30]

In 1879 G. Stoke introduced a no table improvement in the part for the recording that has brought the use of the instrument up to the present day. (Figure 3B) [8], [21]. The instrument, which had a great diffusion, consists of a glass sphere, which operates as a converging lens, mounted concentrically to a spherical metal section. The diameter of the section is set such that the sunrays are focused on it during all the apparent daily motion of the Sun. On the metal section there are three guides placed at different heights on which a strip of chart paper is inserted, different for each season. When there is sunshine, the path of the Sun is marked on the strip, through the burnings due to the sunrays concentrated by the lens. The sum of the burning lengths on the chart paper indicates the daily sunshine. The instrument requires daily the manual replacement of the paper strip. [8].

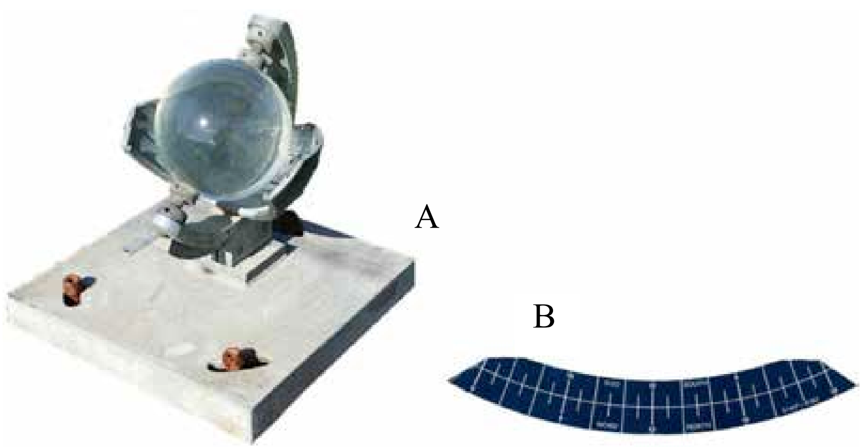

Figure 3.B - Campbell's sunshine recorder (A) with Stokes's support for chart paper (B), 1879. Photo by Gianni Fasano.

In 1888 J. B. Jordan, after design various prototypes, proposed a photochemical effect sunshine recorder. The instrument (figure 4) consisted of two semi-cylindrical chambers of blackened metal with an axis oriented parallel to the earth's surface and with a thin slit in the center of each one flat face. Strips of photosensitive paper were placed on the internal cylindrical surface of the boxes, so that the sunlight penetrated by the two slits left a mark. The boxes were arranged so that one was active in the morning hours and the other in the afternoon hours [21] [28].

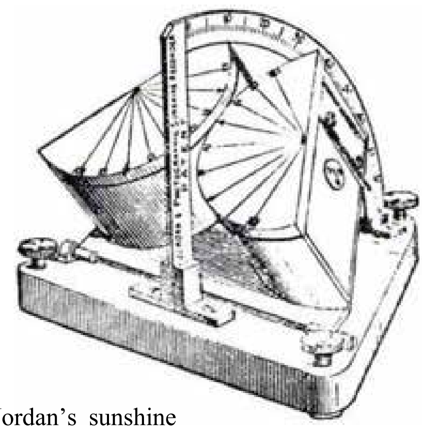

Figure 4 - Jordan's sunshine recorder (1888). From [21].

In the second half of the nineteenth century the *Arago actinometer* was developed. Although there is no reference to this instrument in the works of J. D. A. Arago, in his collection of scientific instruments H. Marié-Davy found a prototype. [10]. It is also known as the *Arago-Davy actinometer* since Marié-Davy used it for his measurements at the *Montsouris Observatoire* and described it in a work of 1875 [12]. The Arago actinometer, similar to the instrument described by Saussure, was not particularly precise as it was pointed out by several scholars as early as the beginning of the 20th century [3] [9]. In particular, the instrument suffered from a gradual decrease in sensitivity due to the loss of transparency of the glass casings where the thermometers were enclosed (about 20 % in 8 years) [9].

Towards standardization

In 1879 the Second International Meteorological Congress, held in Rome which led to the birth of the *Organization Météorologique Internationale* (OMI), established with regard to solarimetry that research on solar radiation was not yet sufficiently detailed to be able to propose adequate observation methodologies. In 1896 in Paris the OMI appointed a Commission for Solar Radiation with the task of establishing a standard for measuring instruments and procedures. In 1905 in Innsbruck, in the Third Conference of Directors of National Meteorological Services, it was decided to take as the reference standard the Ångström pyrheliometer (Figure 5), instrument still used today [2], [15].

Other instruments were designed and built in those years; in 1896 V. A. Michelson built a pyrheliometer more precise than Pouillet's, based on an ice calorimeter, but impractical to use. In 1908 Michelson made a bimetallic one with a thermocouple thermometer which, although calibrated with reference to a standard pyrheliometer, was much more easily transportable and usable [19].

In the following decades, different types of radiometers were designed to measure the other components of solar radiation (i.e. the pyranograph by M. Robitzsch in 1932) which started the built of instruments whose signal could be recorded analogically on a system of data acquisition (in general a chart recorder).

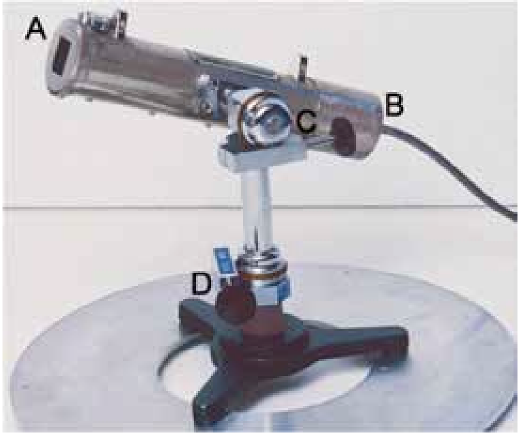

Figure 5 - Ångström's pyrheliometer (1893). In the current version, the instrument is a tube about 25 cm long, with an opening approximately equal to the solid angle within which the Sun with its halo can be seen from Earth.
A: open end; B closed end. C and D gears to orient the instrument so that the end A is orthogonal to solar radiation. In figure, the orientation is manual, but the instrument can be equipped with a solar tracker to automate its continuous alignment with the Sun. Photo by Gianni Fasano.

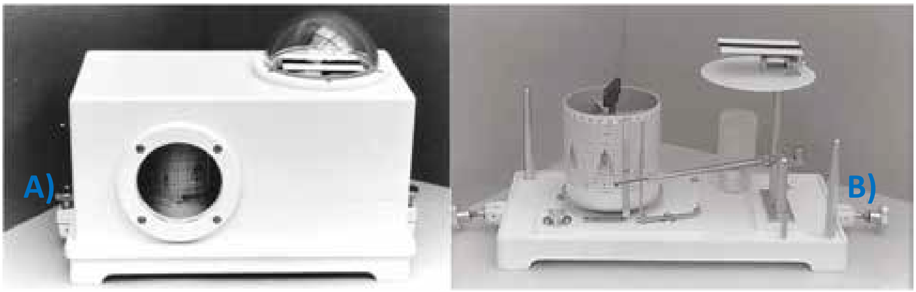

Figure 6 - Robitzsch's bimetallic pyranograph (1932): external view (A) and internal view (B). Photo by G. Fasano.

The Robitzsch pyranograph (figure 6), an instrument for measuring global radiation, had three bimetallic blades side by side as sensitive elements: the central one blackened and the side whitewashed. The blades were arranged so that the thermal deformations (due to solar heating) of the white ones acted on the movement of the pen, in the opposite direction to the action of the black blade. The recording took place on paper, mounted on a rotating drum and was traced by an ink pen. The instrument was equipped with a spring-loaded mechanical clockwork.

In the same period, pyranometers were made (figure 7) to measure the intensity of radiation through the electric potential difference generated by a Moll-Gorczynki thermopile, designed in the 1920s; other types were built using a photocell[4] as a sensitive element. Versions of these instruments were made to measure the diffuse component of solar radiation where the only difference, with the apparatus for the global component, was that the sensor was shaded with a band that had to be adjusted every two to four days in relation to the season.

[4] Photocell: electronic device, based on the photoelectric effect, which converts radiant energy (in solarimeters, solar energy) into electrical energy.

Figure 7 - Current version of pyranometer (Eppley model PSP, 1957): on left for global radiation; on the right the same instrument equipped with a shading band for the measure of diffuse radiation.

F. Albrecht, in the early 1930s, proposed a pyranometer (*pyrradiometer*), for the measurement of total solar irradiance (total solar radiation) [14] which had as its sensitive part a blackened thin metal disk surrounded by a coplanar ring; the two elements were connected by a thermoelectric battery composed by a series of elements of manganin-constantan thermocouples. The sensor was protected by a spherical cap inside which there is very rarefied dry air [26]. In the same period, for the measure of net solar radiation[5], Albrecht designed a net pyranometer *(net pyrradiometer*) based on the same principles, but which used two blackened plates. In 1952 Hofmann proposed a modified version and later the measurement method, by means of two blackened and thermally insulated plates, was adopted for many of the modern net pyranometers [14].

OMI, WMO and networks of measurement stations

One of the first recommendations for radiometric measurements was given during the X meeting of the International Meteorological Committee (Rome, 1913) where it was established that *the measurement of the total radiation of the sun should be made regularly at least once a day at a suitable time, and on clear days as frequently as possible.* [25], [26].

In the Eighth Conference of Directors of the National Meteorological Services (Washington, 1947) it was recommended that each country should establish a network of stations for solar radiation measurements, in order to use for climatological purposes and in other applications [26]. At the same Conference it was recommended that the networks of agro-meteorological stations (their institution were discussed during the conference) should, as far as possible, continuously record data of global solar radiation, in particular within the photosynthetic bands of solar spectrum (Photosynthetically Active Radiation). These bands were specified as red-orange 0,60 ÷ 0,70 μm, blue-violet 0,40 ÷ 0,50 μm and biological ultraviolet 0,29 ÷ 0,32 μm. In addition, it was recommended to include sunshine duration measurement in any solar radiation observation scheme [26].

[5] Net Radiation: radiative flux given by the difference between the radiation coming from the celestial vault and that arriving from the surface under consideration in the spectral range: 0,3 ÷ 60 μm.

In general, the systematic measures of solar radiation began in the second half of the twentieth century. There are few considerable sets of radiometric data before 1950 [12]: only some series of radiometric data collected for short periods (maximum 7-10 years) in some parts of Europe and the Mediterranean basin were recovered. In the period between the two World Wars the most remarkable actinometric observations were conducted by Gorczynsky in Poland, France, and Tunisia.

The developments of the late Twentieth Century

The solarimeters in the second half of the twentieth century evolved from a technological point of view, but they used widely what had been previously designed as sensitive elements (thermopile, photocell, etc.). Technological development allowed to carry out measures in wider ranges of the solar spectrum, or in part of it (such as ultraviolet bands) which until then could not be investigated.

Starting from the last decades of the 1900s, digital recording instruments have also been developed for radiometry. Moreover, instruments have been built that drastically reduce maintenance operations, an essential aspect for measurements of quantities, such as sunshine and diffuse radiation, carried out in remote and difficult to reach sites.

For example, for the measure of sunshine duration, automated instruments have been designed that have photodiodes as a sensitive element. These instruments have a much more accurate time resolution, a much more precise threshold; they also eliminate the daily burden of replacing the chart paper strip as in Campbell Stokes' sunshine recorder.

About ten years ago, a multiparametric electronic radiometer was designed and built for routine measurements that do not require great precision. The instrument has several radiation sensors (photocells) and is equipped with a mask that, during the apparent movement of the Sun, shadows some sensors and others do not (Figure 8). In this way, the shaded sensors measure the diffuse radiation, the others the global one; with these two quantities the radiometer, through its own microprocessor with its own algorithm, calculates the sunshine duration. The instrument supplies three electrical signals outputs, corresponding to three measured quantities,

Figure 8 - Electronic radiometer for the measurement of global radiation, diffuse radiation, and sunshine duration. On left the instrument, on right the shadow mask.

thus allowing continuous recording. Another advantage is that the multiparameter radiometer does not need neither specific precautions for its installation nor periodic adjustments [8].

Solar Radiation and Human Health

In the last decades of the last century, the observation of the increase in ultraviolet (UV) radiation, which reaches the earth's surface, has led many authors to carry out studies on the biological effects that this phenomenon has on ecosystems and human health.

Until 2016, there was no reference standard for the calibration of radiometers for UV measure. Consequently, many existing instruments were not comparable to each other because they were calibrated with different reference systems. [22]. In 2016 the CIE (*Commission Internationale de l'Éclairage*) provided an international standard for the calibration of UV radiometers [20].

Biomedical research has concluded that exposure to solar ultraviolet (UV) radiation can have harmful effects on human health, in particular on the skin, eyes, and immune system [13]. Regarding safeguarding the health of outdoor workers, significant problem for activities in coastal and marine areas, it shows fundamental importance to have an estimate of UV radiation in order to establish the maximum exposure times.

Since in many standard weather stations UV-A (315 ÷ 400 nm) and UV-B (280 ÷ 315 nm) have not been measured, some researchers have carried out models based on artificial neural networks to estimate them starting from the values of the meteorological quantities , most commonly measure [7].

Radiometric measurements for marine and coastal environments

The possibility of life of animals and plants, which have as their habitat the coastal aquatic environment, is linked to the capacity of solar radiation to penetrate in the water column, in quantities and qualities that guarantee the metabolic activity of marine and lake organisms. Hence it is important to have instruments, spectroradiometers, for measuring the radiation that can penetrate sea water in its double quantitative and qualitative aspect depending on the thickness crossed.

Penetration, selective absorption of solar radiation and transparency of sea water are indicative of biological activity and suspended matter. *In situ* measurements of both transparency and water absorption can be carried out using instruments, such as the underwater radiometer and the Secchi disk, which measure the level of radiation reaching certain depths. The underwater radiometer records the intensity of radiation in the ultraviolet, visible and infrared ranges of the solar spectrum, down to the depth of a few hundred meters.

The Secchi disk is an instrument for measuring the transparency of the water column. This device was invented in 1865 by Father Angelo Secchi, who used it for the first time during a cruise of the *Immacolata Concezione* pirocorvette in the Mediterranean Sea. It is a circular disk, about 20÷30 cm in size, white or with alternating white and black dials. The disk, suitably weighted, is sunk by means of a cable on which marks corresponding to the depth are shown; the measure consists in detecting the depth at which the disk becomes barely visible. The greater is the depth value read, the greater is the transparency of the water.

Many underwater radiometers have been developed over the years, some with a unique spectral band [24], others with multiple bands, but very narrow [31], some finally providing a continuous spectrum [23]. These instruments, even the simplest ones, are characterized by a rather high cost; this is partly due to the fact that they provide the absolute value of the incident radiative power for the various wavelength ranges or for the different spectral lines.

Also in the 2000s, for studies concerning both physical and biological marine and oceanic quantities, devices were carried out for the qualitative and quantitative measurement of solar radiation that can penetrate, at different depths, into sea water [16]. For these kinds of studies, CNR-IBIMET designed and built a benthic chamber that allowed for metabolic measurements of the underwater flora. In particular, through SuMaRad (*Sub Marine Radiometer*, device designed by CNR-IBMET, figure 9) the solar radiation in the water column was measured in the global, blue, green and red ranges, ranges indispensable to the life of underwater vegetation, [16] and by means of a multiparameter probe pH, temperature depth, conductivity and dissolved oxygen were detected [17].

The SuMaRad system measures underwater radiation, at different depths, in four spectral bands, not in absolute value but in ratio to the corresponding solar radiation (pure number between 0 and 1), in the same bands, at the sea surface. The considered spectral ranges are: global radiation (400 ÷ 1100 nm), red (590 ÷720 nm), and blue (400 ÷ 540 nm), that activate chlorophyll *a* and *b*, and green (480 ÷ 600 nm) that is absorbed by some active carotenoids [29]. The instrument indicates, in other words, the transmittance of the water by providing, in reference to the radiative energy that reaches the different depths, comparative data with respect to the energy external to the water.

A pressure sensor and a temperature sensor are installed inside the underwater radiometer, which give indications respectively on the depth and temperature of the measuring point. The operating depth of the instrument is 50 meters.

Figure 9 - SuMaRad and Benthic Chamber, during the installation phase on the seabottom of Cavo (Elba Island-Italy).
Photos by Gianni Fasano.

Conclusions

The history of the design and carried out of instruments for measuring solar radiation for meteorological purposes began only in the first half of the nineteenth century, although this quantity is the main engine of environmental physics and terrestrial biology. More recently, radiometric measurements have begun for research in marine and coastal environments and for studies on the effects of the various components of solar radiation on human health.

As with other instruments for environmental measures, with the standardization of the measurement procedures and with the unification of the new devices, the authorship of these instruments has been lost: the inventor is no longer there, the Campbell-Stokes sunshine recorder or the Robitzsch pyranograph are no longer there. Today there are companies that develop new, increasingly efficient and sophisticated, technological and design solutions whose authors remain anonymous.

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