# Geometrical interpretation of sky light in architecture projects

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## 1. Introduction

Natural light comes from a main source, which is sunshine, and from a secondary source, sky vault, illuminated by the sun, but the latter produces a very different light: lighter, cooler (its spectrum moves towards blue colours) and diffuse (it does not project shadows).

When the sky turns overcast, this light becomes hegemonic and, depending on the type of clouds, uniform or full of changing patterns. In the North of Europe, low sun and cloudy sky are usual, and diffuse light has been a recurrent theme for painters – from the Dutch school till the impressionists – and an evident appeal for architecture – zenithal light of Alvar Aalto, for example.

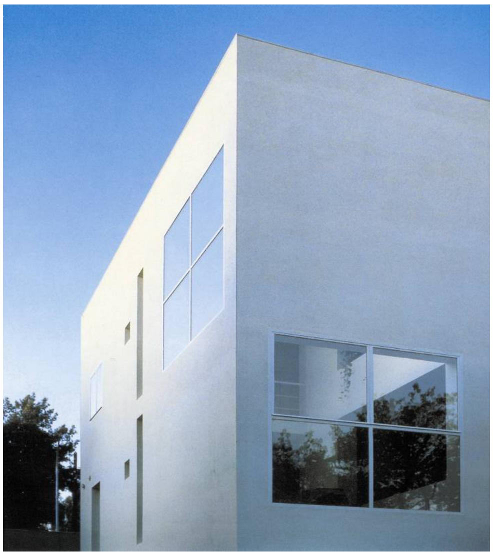
Nevertheless, it is in the Southern countries where sky light should offer a determinant design criterion for the project of architecture. The Northern solar radiation is always welcomed, indeed, and simple curtains can eliminate the visual trouble of lower and more penetrating sunbeams. On the other hand, protection from summer heat becomes necessary in the Mediterranean climate and sun radiation is a whole year enemy in the tropical regions. Thus, once the sunbeam is maintained out of Architecture, buildings only dispose, for their illumination, of casual reflections on the ground, on vegetation or on others buildings, and of sky light, on top.

This diffuse light offers important advantages with regard to the artificial one: it is free, its variation is generally appreciated, and, moreover, it has an excellent luminous efficiency (until 150 lumens for any Watt of solar energy). That is, for the same quantity of light it heats much less than the incandescent lamps, and twice less than fluorescents (efficiency is about 75 lm/W) [1].

Here, we will talk about blue sky, once the sun is masked, and about how we can aid the designer to open the project to it, by means of Descriptive Geometry, through its clear representation.

## 2. Representation and design

### *1st picture: Casa Turégano, outside*



In this first picture, that represents a house of the architect Alberto Campo Baeza, we can see the four components all together of the natural illumination: sun light, sky light, specular reflection and diffuse reflection.

It is a photograph but it could be a hyperrealist painting or a render, as well. Nowadays, it is no longer difficult to obtain this level of "photographic realism" with software.

Unlike painters, that do not need to distinguish with so much rigour the different aspects of illumination, the digital mock up designer "is painting with parameters", adjusting the different values that regulate the simulation. Direct light and specular reflection can be calculated with a simple ray tracing [2], but diffuse light needs more sophisticated algorithms, based on *radiosity* [3]. Owing to the complexity of the resultant hybrid methods, and also to the commercial character of most rendering software, the user knows less and less about the calculus behind, and is only guided by the visual results, and thereafter by previous experience about light appearance.

Although this is a positive and didactic aspect, it cannot help directly in architectural projects. Rendering software are too slow to be considered as design tools (interactivity is not yet conceivable) and their computations lack of the necessary limpidity for a secure interpretation.

***2nd picture: Casa Turégano, inside.***

In this second picture, we can see how the entry of the sunbeam completes the scene equilibrium desired by the architect. The illumination is not only a problem of thermical or visual comfort, but a fundamental part of the composition.

The sun moves throughout the day and year; a double sequence of renderized pictures, or a sequence of animations can show such a variety of paths, but with so diluted information that these representations are impracticable in the design process, when the forms and orientations are still modified: it would be necessary to use a much more synthetic representation of the paths and of their effects. The render programs do not offer it because their main goal is photographic realism [4].

***3rd picture: Casa Gaspar, patio.***

In this third picture, light is very different: the sun, closer to twilight, does not project more shadows in the patio. However, the illumination presents subtle gradations, the same that would be observed with an overcast sky.

It is darker where sky is less visible: at the bottom of the walls, in the corners, in the recesses. Hence, the level of illumination due to the sky at any point of the space is clearly connected with the quantity of sky visible from this point, that is, with the solid angle that embraces the sky from this point (this angle, normalized as a percentage of the complete vault of heaven is called: *sky factor*). It is a very different type of shadow than the one projected by the sun, but no less geometrical. Furthermore: the sky factor does neither depend on the hour nor on the day, on the latitude or altitude: it is a pure geometrical factor.

¿Would it be possible to design with it?

A thermics software, that computes the diffuse light, cannot help with this, because it generally evaluates sky light as a fraction of direct light, not accounting the geometry [5]. Moreover, as rendering software, it is not focused on design, but on analysis.

## 3. A design software for architecture

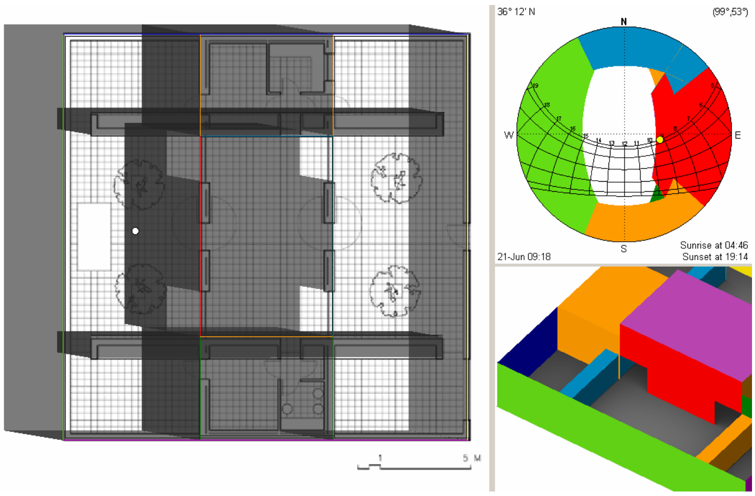
A software dedicated to design must offer computations and representations that should be fast (allowing interactive handling), synthetic (allowing the visualization of all the useful information) and limpid (with unambiguous interpretation) [6].

Since the year 2003, we are developing the software “Heliodon” with the intention to realize a true tool for aided design with natural light [7]. We started with the direct sun light, using the classical stereographic representation.

The stereography gives all the information about sunlight for every hour of the year, but only at a point. In order to interpret it correctly, it is very useful to relate it with a shadowed top view, that shows all the space, but in an instantaneous graphic (the shadows correspond to a determined instant of the day and of the year). Heliodon presents three simultaneous views, completing the information with a 3D view, so that any change in one of them has instantaneous effects on the two others: moving the sun in the stereography, the shadows move in the two spatial views, while any movement of the sensor in the 2D view modifies the masks in the stereography.

This original and simple idea really powers the tool, allowing the user to control the consequences of its changes in the geometric model simultaneously in time and space, each representation compensating the limits of the two others.

In this first step, we achieve the three requirements for a user-friendly design tool: speed, synthesis and limpidity.

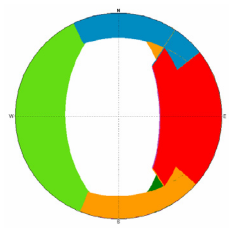



***4th picture:*** Triple window of Heliodon: on the left, shadowed top view of Casa Gaspar, with the sensor (white circle) located in the middle of the patio, near the pool, in the shadow; on top right, stereography corresponding to the sensor, with the sun position (yellow circle) corresponding to the summer solstice in the morning. The Sun remains masked by the red wall, which effectively projects its shadow on the sensor of the top view; these shadows correspond to a determined day and hour. At bottom right, is the axonometric view, the ground is coloured with the sky factors, showing gradations similar to those shown in the third picture.

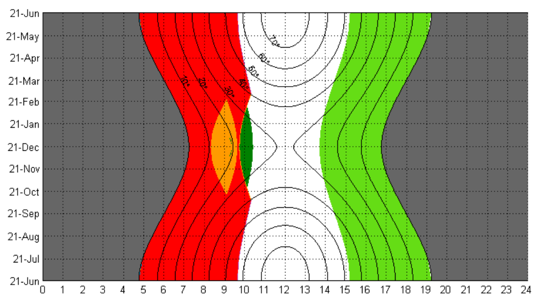
The user of the software quickly discovers that he embraces and understands easily the full sunlight problem and the consequences of his design options, travelling freely in time and space, but he also verifies that it is very difficult to translate this study to a printed document, once the interactivity is lost. Thus, he will need to obtain an even more synthetic representation than stereography. Considering the spatial aspect of this projection, he would like to compare the hidden portion with the visible part of the vault of heaven, but this is not possible, since stereography is not equivalent (it does not respect the proportions between surfaces). Considering the temporal aspect, he would like to compare the hidden part of the sun paths with the visible one, but again it is not possible, because neither the hours nor the months are equidistant.

Consequently, two other projections with different properties are needed.

***5th picture: equivalent projection***



To evaluate the *sky obstruction*, an equivalent projection is needed, where the relation between the free space (not coloured) and the complete disc (the vault) gives directly the sky factor. Sun paths are not represented anymore, because this projection is purely spatial. The computation is immediate; in this example, the sky factor is equal to 38%.

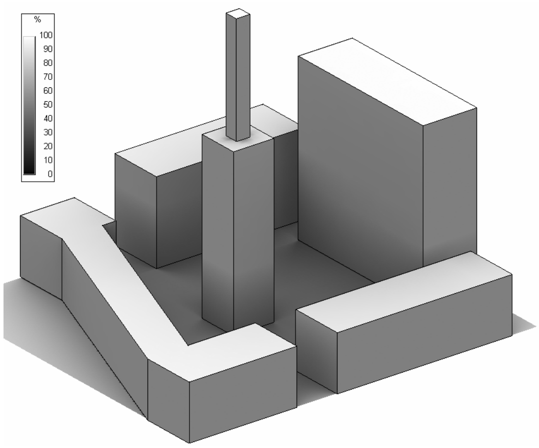



***6th picture: isochronal projection***

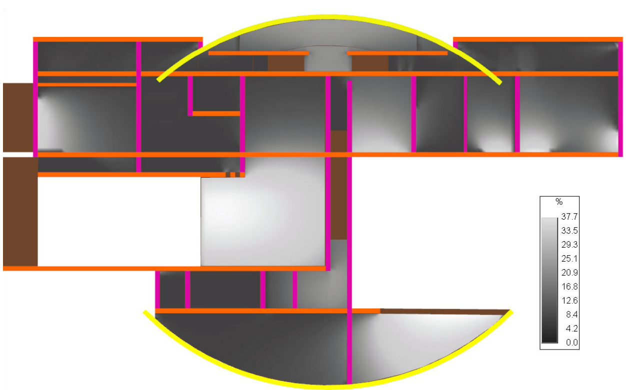
To evaluate the daily, annual or seasonal duration of sunlight at a point, we had to invent a new projection, which we called *isochronal*, because in this graphics hours (horizontal axis) and months (vertical axis) are equidistant, fact which allows integrating the sunlight duration in intervals defined by the user [8].

These two projections can be evaluated on arbitrary plane sections, yielding to sky factors or sunlight maps. The sunlight case has been described in another publication [8]. Here, we will concentrate on the problem posed by the sky factors, and by the diffuse light of the sky. We have observed, at this stage of the application process, that the user is accepting to loose interactivity because he is gaining more synthetic representations. This will allow him a better control of his work and to present some consequences of his advanced design.

## 4. Sky factors




We can colour entirely the surfaces of a scene with the sky factors, as in the next picture of an imaginary square. The quality of the resulting gradations is amazing: they appear as a very refined render, where the feeling of depth is reinforced in the axonometric projection. Nevertheless, this picture only exhibits geometrical information: the highest roofs are white (sky is totally open), and greys become darker when the sky is masked, with subtle point-wise effects on the ground, near the salient corners.




The top views darkened in this manner are of particular interest, as in this house by Tadao Ando [9] where the shadows representation derived from the entrance of natural light is highly suggestive. Many architecture sketchers usually draw their top views with shadows projected by sunshine. They appear on the ground proportionally to the different heights, by oblique projection. However, these shadows only correspond to a brief instant of the day and year. That is why they are arbitrary somehow. Besides, although they enrich the information of the top view, they deform it, superposing lines to lines, as well. The sky shadows do not present such defects and reveal different, very interesting, information: they reveal the apertures and their importance, the patios and their deepness, the spots more or less open, the bottom of the high walls… they do not talk about magnitudes, but about relations.

At this point, the question is: shall these sky factors, so easy to calculate and to interpret, allow to quantify the diffuse light and to participate to an energetic evaluation?

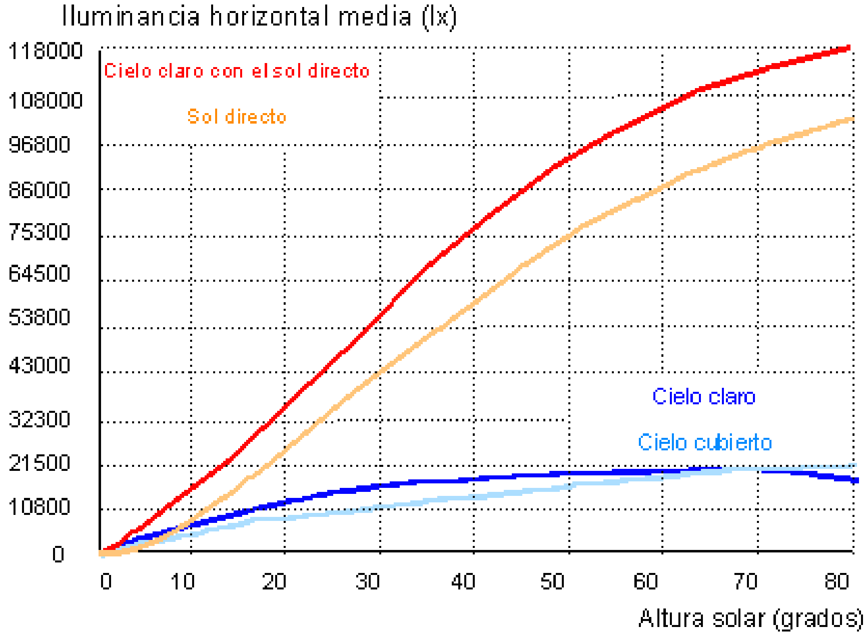
## 5. The light on the surfaces

Various normalized models offering luminance maps of the vault of heaven [10] are available to compute the sky contribution in diffuse light. The problem is that sky luminances and their spatial distribution vary a lot in function of the atmospheric conditions. The idea of a uniform sky seems to correspond very well to the tropical cloudy sky. Other models describe the overcast sky as three times more luminous at the zenith than on the horizon. Blue sky (in the shadow of the sun), which is our present concern, is more complex: it has its minimum close to the zenith, at the opposite of the sun, a more luminous crown close to the horizon and, obviously, its maximum near the sun, although not taken into account. This model is leading to heavy computations, however; it depends on the sun height and strongly interacts with the many configurations of the sky appearance. Here we do not want to consider such complex problems; we rather prefer to think first about the possible uses of sky factors.

Another, more practical, way to study this problem consists in measuring, under determined conditions, the response of a luxmeter maintained horizontally in a fully open place. This is what is proposed in the following diagram [11].

The two inferior curves give the values in lux of the sky illuminance on a horizontal plane in function of the solar height in two extreme conditions: clear sky (in blue) and overcast sky (in cyan).

The maximum value is 20 000 lux (overcast sky with quasi zenithal sun); an overcast winter sky could give about 10 000 lux, a summer clear sky about 15 000 lux.




The question of interest is: how much shall we measure with a luxmeter in a street or inside of the projected building? At first sight, the sky factor could give the answer, because it indicates the visible proportion of sky for the selected point. However, after analysing the diffuse light properties, we deduce that it is not correct, even for a uniform sky.

We need to consider the radiosity equations to solve the problem completely. They allow us to compute the illuminances on each surface of the scene taking into account the interactions between all the objects. In this method, we express the radiative equilibrium, considering that the radiosity of a small area is the sum of its proper emission and that of all the radiosities emanating from the other visible elements and those reflected on this element [3].

Such perfectly realizable computation needs to introduce a great number of physical parameters, however, and, since all the possible interactions between the plane elements constituting the scene must be considered, the process is very long and requires the use of complex algorithmic techniques. A computation of this nature can be very useful for the analysis but totally inoperative in the stage of design, not only because it is very slow, but because it requires defining with precision the optical characteristics of all the materials. This often results difficult in the first steps of the design.

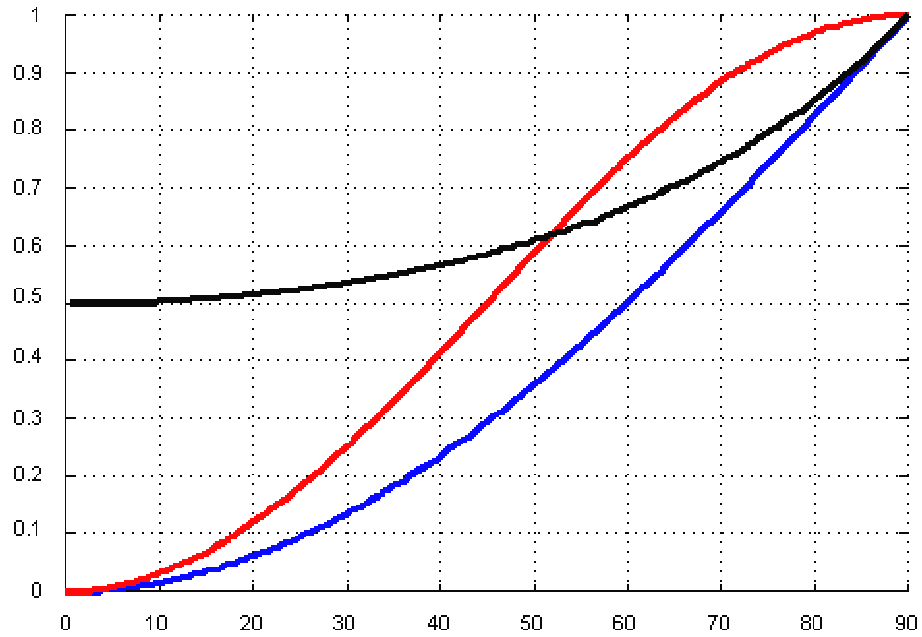
However, here we are only interested (by) in the diffuse sky light, and we avoid diffuse reflection. We assume then that all the obstructions of the scene are very dark, and absorb completely the incident light. In these conditions, we will study the simple case of the interaction between a plane element of the scene (the luxmeter) and the sky, partially obstructed by the objects of the scene.

In the *method of radiosity*, the interactions between the different elements are described using a pure geometrical expression called *view factor* (or *form factor*). This term, resulting of a double integration on two elements in relation, is proportional to the cosines of the angles formed by the beam with the perpendiculars to the two surfaces, and inversely proportional to the square of the distance between them. Its physical meaning deduced from the properties of the radiative exchange, is that it represents the proportion of the total power leaving the first element and received by the second one. It can be shown, using the Nusselt analogy [3] [4], that this factor can be evaluated very simply by projecting orthogonally the spherical projection of the masks on the studied plane: the relation between the representation of the sky surface and the disc surface gives precisely the *punctual view factor*. This observation is very important for us, because Heliodon software already evaluates the sky factor using an azimuthal equivalent projection; it is enough to substitute it with an orthogonal projection to obtain the view factor.

In the case of a uniform sky, the *view factor* applied at a point on a surface and at the visible part of the sky will directly give the relation between the illuminances that correspond to the complete vault of heaven and to its not obstructed part.

Now, we will compare the view factor with the sky factor in two examples.

- *Comparison between the sky factor and the view factor calculated on a horizontal plane, for a zenithal portion of the vault of heaven, which opening varies between 0 and 90°.* We can imagine ourselves moving from the bottom of a well with circular section upwards until reaching the surface. The well orifice can be considered as the base of a cone with an angular opening increasing from 0 (at the bottom) to 90° (at the surface). According to their definitions, the two factors vary from 0 to 1, but following rather different laws. For little openings, *the view factor is twice superior to the sky factor*. This property is general for zenithal portions of the sky (up to an opening of about 20°). In the zenithal zone, in effect, the relation between the equivalent projection of the hemisphere and the orthogonal one equals two.




View factor (red) and sky factor (blue), relation between both of them (black), for a portion of sphere

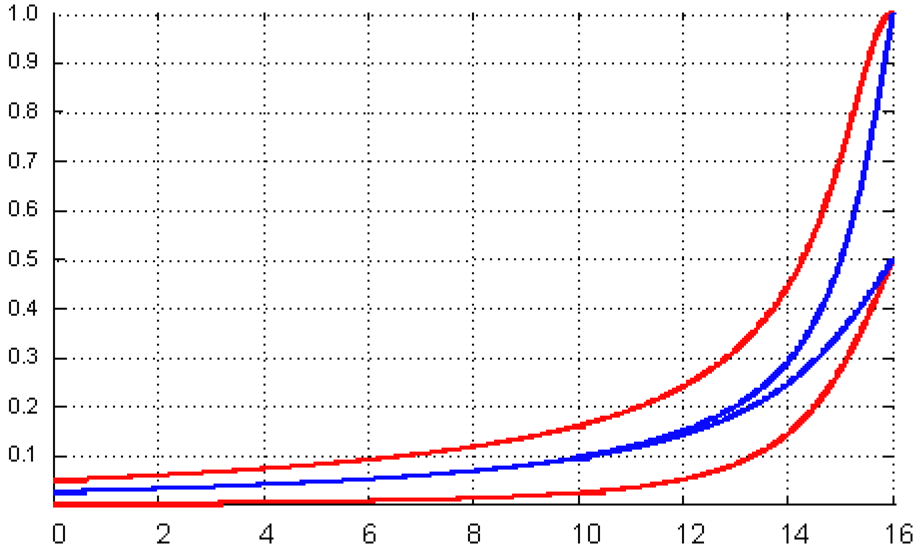
- *Comparison between the two factors in a parallelepiped cavity.* We can imagine ourselves now at the bottom of a straight lane with both ends closed, 2 metres wide and 32 metres long, bordered by a five-storey building (16 metres high).

We first produce a computation at ground level, at the centre of the lane. The sky factor and the view factor respectively measure 0.028 and 0.051. As in the previous case, standing at the bottom of a deep cavity, we verify that the view factor on a horizontal surface doubles approximately the sky factor.

In the next graphic, the view factors (in red) are compared with the sky factors (in blue). The upper curve shows the view factor evolution on a horizontal surface moving upward in the centre of the street. It varies from 5% at the ground level to 100% at the roofs level. The second curve shows the sky factor evolution calculated in the same points. It varies from 3% to 100%. In all the lower part of the lane, it is half the horizontal view factor.

The two inferior curves represent the same factors calculated on a vertical plane located on one of the façades. Here, the view factor is calculated on a vertical plane. As expected, both factors tend towards 50% at roof level (the same wall where these are calculated masks half of the sky). In the lower part of the lane, the sky factor is more than ten times superior to the vertical view factor.

It is interesting to observe that the sky factors curves are located between the two view factors curves.



View factors in red and sky factors in blue (centre and façade)

For the energetic computation, only the view factors are correct. So, assuming that the totality of a uniform sky produces an illumination of 20000 lux in a horizontal luxmeter, and then locating this luxmeter in the centre of the obscure lane at ground level, we will measure about 1000 lux, while maintaining it at the same level, but vertically, against a façade, we will only measure 0.0032 * 20000 = 64 lux. The façade illumination will only reach the lane ground one at a height of about 12 metres.

This corresponds to experience: when we want to read a book in a narrow lane where sunshine is not entering, we have to maintain it horizontal, towards the sky. If we place it vertically, the pages seem too dark (obviously, the situation will change considerably if the façades are clear, providing multiple reflection). The *view factor* reflects this situation; the *sky factor* does not, because it is not concerned with the surfaces orientation. It is inadequate for an energetic computation, even an approximated one.

However, in a global consideration, the sky factor is not inconsistent: its values are situated between the illuminations of the two extreme cases (the horizontal plane and the vertical one), and it makes the contrasts smooth. The previous graphic explains why the visualizations of objects painted with sky factors as shown before satisfy the eye.

## 6. Light and volume

Therefore, the radiative computation is always produced on oriented surfaces, using view factors because it is by means of surfaces that objects in the scene exchange energies.

But the energetic approach is not enough for architecture. Firstly, because architecture is not only concerned with the thermic balance, but by the *perception* of the energies, as well. In second place, because this perception does not depend only on the physical data, but also on their cultural and aesthetical evaluation.

We should always remember, when talking about visual perception, that the eye *foreshortens the luminous intensities* [12], applying to them a logarithmic filter that should be considered in the photometrical magnitudes, as the acousticians do with sound intensities expressed in decibels. But the fact that the eye also exhibits certain constancy and interprets continually all it perceives, is important, as well.

An illustration of this is the *daylight factor*, used in some norms about natural illumination in architecture. It is defined as the illumination in the considered building divided by the illumination in the same location but in an open spot. Indeed, many studies have shown that the visitors of a building value its luminosity with total independence of the atmospheric conditions and, therefore, their valuation depends only on the perception of the architecture: its geometry and the optical properties of its materials [13].

But we should go further and begin to think properly about volume. The Californian artist James Turrell has observed that “we have been a culture of surfaces in such a way that we have never really looked to light; we have only looked to the painting, to the things, although this is changing now” [14]. In its more beautiful works, as the “Deuce coop” in Barcelona, he managed to erase the surfaces, submerging the visitant eye in a light volume without frontiers. The architecture, always depending on natural light, does not enjoy the same freedom allowed by the intensive use of artificial light, but I believe that architects like Peter Zumthor or Alberto Campo Baeza pursue similar intuitions in their more recent works.

Hence, a tool able to help in such designs would be in need. And it is here where sky factors are of interest: by definition, they qualify the volume (and not the surfaces), where they vary smoothly, indicating the direct relation between sky and geometry. And that without considering the reflection, that is, the result does not depend even on colour of surfaces; only on form.

Therefore, we intend (think) to integrate in a near future the development of Heliodon software, a computation of these factors on a 3D mesh. Thus, we could determine the proportion of the interior volume of a building where the sky factor is superior to certain value. This new parameter would allow us to compare very different buildings (for example: a series of gothic cathedrals or a set of modern houses), without needing to know their finishing, orientation or geographical location.

As such, we will compute an aspect that cannot be represented, given that we can only draw surfaces, but that corresponds to the three-dimensional nature of architecture, as we perceive it with our eyes, that are not surfaces, but complex organs, active and restless, that are continuously moving, in middle of the fluxes of light. Forming. Informing.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