DESIGN OF ANIDOLIC ZENITHAL LIGHTGUIDES FOR DAYLIGHTING OF UNDERGROUND SPACES

Simone C Molteni, G. Courret, B. Paule, L. Michel, J. L. Scartezzini
Solar Energy Laboratory, EPFL, CH 1015 Lausanne, Switzerland,
tel. +41-21-6935557, fax. +41-21-6932722, Simone.Molteni@epfl.ch

Abstract – Due to the congestion of contemporary large cities, the exploitation of the basement is strongly increasing. This is why, after subways and car parks, new public spaces like concert halls and auditoriums are getting common in downtowns' basements. For this kind of building typologies, where windows are inadequate and skylights unsuitable, zenithal lightguides can be used to provide daylight. Their luminous performance can be improved by using sunlight trackers or static concentrators, which generally reduce the incoming of daylight during overcast conditions. The theory of anidolic optics (non-imaging optics), was used to overcome this difficulty. Scale models were used to assess their performances thanks to a scanning sky simulator. It was shown that the adjonction of an anidolic element to a plain zenithal lightguide improves its luminous performance: it provides an optimal concentration of sunlight for clear sky and a moderate reduction of the illuminance for overcast conditions. User-friendly abacuses were set up to support the design of anidolic zenithal lightguides in practice, including the shaping and the dimensioning of the device.

1. INTRODUCTION

Since the Industrial Revolution, the discovery of new building materials and technologies has allowed the realization of projects which were considered unfeasible in the past. Nowadays, underground transportations and car parks, as well as skyscrapers and huge buildings, are common urban typologies.

Modern downtowns being fully exploited in large cities, the need of new spaces leads to a higher exploitation of the underground, where space appears endless. Public car parks and underground stations, but also shopping centers, concert halls and offices, are consequently partially or totally placed underground.

Lighting is, of course, one of the biggest problems to be solved in these cases. Since vertical openings are insufficient or not feasible and skylights often unsuitable (multi-storey buildings or thick structural slab, i.e.), artificial lighting is generally found as the unique solution.

Daylight can offer, on the other side, much more than simple energy savings: it corresponds to a physiological need for human beings. Natural light stimulates hormonal regulation, provides significant relief of the feeling of isolation (Bouchet and Fontoynont, 1996), has good effects on some physical and psychological diseases and assists people in shift and computer VDU work (Liberman, 1991).

Adequate visual comfort has sometimes a relevant cost but leads to increased motivations and productivity in work. Smiley reports that students attending a daylit school achieved better examination results (14 % higher marks) and higher attendance rates than those in non-daylit schools, including newly built ones (Smiley, 1996).

Zenithal lightguides can provide a significant contribution of daylight in buildings where no direct communication with the outside is available.

Even if lightguides, whose dimensions are comprised in between those of narrow and long lightguides (daylight chimney) or large and shallow lightwells (daylight shafts), are characterized by important losses (internal reflections absorb an important fraction of the entering light flux), they lead to sufficient horizontal illuminance into underground buildings, in case of high external illuminance (tens of thousands lux), even for modest daylight factor values (1-2%).

2. MAIN FEATURES OF LIGHTGUIDES

A lightguide is schematically constituted by 3 main elements: the external collector, the funnel and the internal diffuser (see fig. 1).

Figure 1. Schema of a lightguide (Fontoynont and Paule, 1988).
Their corresponding tasks are respectively:

1) the collection of the daylight flux;
2) the transportation of the flux;
3) the distribution of the flux into the building.

Each of these elements can have different shapes, but internal surfaces should always offer a high coefficient of reflection (anodized aluminium or plastic films providing total internal reflection, for instance).

The collector can considerably improve the lightguide performances, allowing a rather high concentration of the light flux at the entrance.

The funnel can be straight or curved; its section can have different shapes. Its efficiency depends on many parameters, like the aspect ratio, the section geometry and the internal reflectance. A simple equation that may be used to estimate the transmittance of a lightguide (without collector nor diffuser) is given by Zastrow-Wittwer (Zastrow and Wittwer, 1987) as:

$$ T = R \quad \text{Eq. (1)} $$

where:

- $T$ is the length of the lightguide,
- $d_{\text{eff}}$ is a generated diameter depending on the section shape ($d_{\text{eff}} = \frac{\pi d}{4}$ for a circular funnel of diameter $d$).

The diffuser contributes to redirect or distribute the light more uniformly in the room and has, then, a secondary role in determining lightguides’ performances.

On the top of the lightguide, a transparent dome or a glazing is also placed in order to avoid rain and dust penetration. Its presence obviously influences the lightguide performances, since even transparent layers partially reflect and absorb solar rays.

In order to focus on the most important elements of the system, lightguides are always considered in this project without diffuser nor transparent closing; depending on the solutions adopted, therefore, the illuminance levels presented here would be slightly reduced in the reality. It is believed, however, that the luminous performance achieved without these elements are significant enough, to justify this assumption.

### 3. EXTERNAL COLLECTOR

Different sorts of collectors can be found in the state of the art. They can be fixed or mobile mirror systems, that allow sunlight to be piped into the lightguide. Many different shapes can be found, depending on the goal to achieve. Barcelona’s building “Club Desportes Hispano-Franzes”, for example, has lightguides equipped with collectors rejecting sunlight in summer (high risk of overheating) and accepting solar rays in winter or mid-seasons. These collectors, adapted to the warm local climate, are made of 3 plain mirror surfaces whose tilt angles redirect solar rays into the funnel and in a direction parallel to its axis (to achieve a minimum number of reflections) only on the winter solstice at 9 a.m., 12 a.m. and 15 p.m. At summer solstice, on the other hand, no sunrays are allowed to enter.

While this kind of collectors are mostly used to select sunlight (i.e. the period when sunlight can enter), others can also perform light flux concentration to rise the daylight flux entering in the lightguide.

For Central Europe climates, characterized by frequent overcast conditions, the use of external concentrators could seem not fully appropriate, a plain zenithal opening achieving better luminous performances than a concentrator in case of a perfectly diffuse daylight (Molteni 1999).

The aim of this work was to design an external collector, whose luminous performances are satisfactory for all year round, achieving an optical geometric configuration for both clear and cloudy sky conditions.

The deliberate choice of a fixed external system clearly makes the problem more complicate, when compared with a mobile tracker. This feature is essential, lightguides being at the end integrated into a building. As a building component, the cost and the frequency of its ordinary handling should be minimized; its life cycle must be comparable with the building one (at least 10 years). Mobile systems necessarily need mechanical and electric components that cannot fulfill these conditions, even if, for a specific sun position, they can provide better instantaneous performances.

Following other applications in the field of daylighting (Courret, 1999) and solar concentration (Welford and Winston, 1989), the theory of anidolic optics (non-imaging optics) was used to design the external collector, accounting for its capability of concentrating daylight in a very efficient manner. The method used to design these collectors is given hereafter.

### 4. DESIGN OF ANIDOLIC COLLECTORS FOR LIGHTGUIDES

CPCs (Compound Parabolic Concentrators) are systems that allow transmitting a determined rectangular optical extent with a moderate number of internal reflections, allowing to achieve an optimum light flux concentration.

The CPC’s acceptance sector is chosen as the first step of the collector design (in the meridian section it is defined by two angles $[\theta_{\text{in, sup}}, \theta_{\text{in, inf}}]$), defining the part of the sky which is accepted as light source.

Rays entering with an inclination included in this range will be transmitted through the CPC within a given angular interval $[\theta_{\text{out, sup}}, \theta_{\text{out, inf}}]$, while all the others will be reflected back to the entrance.

For classical symmetrical CPCs, characterized by a maximal exit angle of $\pi$ radians, the concentration factor $C$ is given by the following expression:

$$ \sin \theta_{\text{in}} \quad \text{Eq. (2)} $$

where the acceptance angle is $2 \theta_{\text{in}}$ (Winston and Welford, 1989).

This means that higher concentration factors are obtained for small values of $\theta_{\text{in}}$. Small $\theta_{\text{in}}$ values make the collector cumbersome and accepting light from only a small part of the sky (defined by an angular opening of $2 \theta_{\text{in}}$).
Two categories of anidolic collector were designed, with the following acceptance angles:

- Series (1): [15°, 95°];
- Series (2): [15°, 67°].

All profiles in both series are made of classical CPCs (exit angles are equal to \( \pi/2 \)); all collectors are oriented towards South to view the solar trajectory. The lower admission angle (15°) is chosen because obstacles are common in urban contexts and, in any case, luminances are weak near the horizon.

Fig. 2 shows the anidolic collector profiles corresponding to series (1).

The first series has a larger input angle and can transmit rays coming also from the zenith, where, for a “CIE overcast sky”, the luminance is 3 times higher than on the horizon. Since collectors should be at each moment pointed towards the strongest sky luminances, this first series viewing the zenith supplies higher lighting levels for overcast conditions, comparing with series (2).

The second series (see Fig. 3), is more aiming at collecting direct sunlight. Actually, the higher acceptance angle of 67° corresponds to the maximum solar height (noon time, at
summer solstice) observed at a latitude of 47.5 LN (Lausanne, CH).

The acceptance range is smaller, inducing a higher concentration factor (see table n. 1). This solution presents in consequence better performances for clear sky but lower ones for overcast conditions.

<table>
<thead>
<tr>
<th>Collector Type</th>
<th>Concentration of Series n. 1: 15° - 95°</th>
<th>Concentration of Series n. 2: 15° - 67°</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>2.06</td>
<td>4.86</td>
</tr>
<tr>
<td>3D</td>
<td>2.44</td>
<td>5.31</td>
</tr>
</tbody>
</table>

Table 1. Concentration Factors [-] of the different collectors designed.

Thanks to the edge rays' principle (Ries and Rabl, 1994), the design of particular CPC profiles is reduced to a bidimensional geometric problem, where only two edge rays (corresponding to the two acceptance angles) have to be taken into account. Applying CPC profiles to lightguides, of course, means transforming this bidimensional profile to a tridimensional shape. Two solutions were considered, each one involving constraints on the funnel section form. The first solution (from now on the “2D” solution), consists in extruding the CPC profile and closing it with two plain mirrors: in this case the funnel section should be rectangular (or squared).

The second solution (from now on the “3D” solution), needs a symmetrical CPC profile, made through a 360° rotation around its symmetry axis. This solution leads to a truncated revolution paraboloid, where entrance and exit surfaces are circular and parallel. The funnel section should then be circular too and a connection device should be foreseen.

In the 2D solution the CPC profile can be asymmetrical (see Fig. 2 and 3) and then designed directly on the funnel upper surface: in this way, no connection device is needed (but notice that in this case the pipe section needs to be either square or rectangular).

In the 3D case, two tilted circles (the collector exit surface and the funnel entrance area), have to be connected with minimum light losses (i.e. no light ray should be reflected back and useless internal reflections should be avoided). The geometrical solution of this problem is given by a truncated portion of torus. The virtue of rotational symmetry allows to reject no radiation, even if the incoming radiation is almost completely diffuse (Collares-Pereira & others, 1995).

4. EXPERIMENTAL VERIFICATION

Scale models of the different lightguides were realized in order to test their performances under different sky conditions. This task was carried out using a scanning artificial sky of new generation (Michel 1997).

2D collectors were realized with a foil of anodized aluminium (reflectance: 90%) and wood layers for the profiles cuts. 3D collectors and torus sections were realized thanks to a computer-controlled lathe working on aluminium blocks. Worked surfaces have then be smoothed with glass paper and polished with a solvent in order to attain a better reflectance.

Scaled funnels of many different aspect ratios were realized, both with a square section (to be used with 2D collectors) and circular section (to be used with the 3D collectors).

The different lightguides were tested following two main goals:
1) to compare their performances (varying the collector and the aspect ratio);
2) to supply a method to design lightguides.

Two kinds of indicators were assessed experimentally: candlepower distribution at the exit plane of the zenithal lightguide and illuminance profiles on the ground.

5.1 Candlepower distributions

In order to get this first performance indicator, a simple device had to be manufactured (see fig. 4). It consists in a quarter of a circle inside a cubic box having totally absorbing internal surfaces (black velvet, reflectance < 2 %). Eight sensors (illuminance-meters) were fixed on the circle with constant angle step (12.78°). A hole was made on the top of the cube where the exit area of a lightguide mode was positioned, allowing its exiting light flux to enter the cube.

![Schema of the « photogoniometric cube » realized. This device has totally absorbing internal surfaces and was used to get the candlepower distribution of lightguides models](image)

The proportion of the hole side and circle radius (their ratio is equal to 1/8) was considered sufficient to consider the hole as a point source. The intensity of the flux was obtained directly from the illuminance measured by the sensors, thanks to the following relation:

\[ I_k = E_k \cdot K \]

Eq. (3)
where:

- \( I_k \) is the intensity emitted from the exit hole in the direction relative of the luxmeter \( k \).
- \( E_k \) is the illuminance [lux] measured by the \( k \)-th sensor.
- \( R \) is the circle radius (i.e. the distance from the hole, constant for all the sensors).

When the emitting source (i.e. the exiting surface of the lightguide) is not lambertian, several measures were necessary to have a complete spatial description of the light flux. When a simple circular lightguide without collector is tested under a symmetrical sky (isotropic or CIE Overcast sky), a single measure is sufficient. If the lightguide is not symmetrical (presence of a collector, f.i.) or the sky is asymmetrical (in case of a clear sky, f.i.s), several measures must be performed because every meridian of the hemisphere behaves differently. In these complex cases, however, only some relevant sections or meridians were considered.

Once these candlepower distributions are available in an adimensional form, any lightguide can be described as a single light source. Then it is possible to use a lighting software to calculate the corresponding performances, like the illuminance in a particular room. This kind of simulations would allow a precise description of a specific building: exact photometrical data (such as furniture and wall reflectances), and their performances of a lightguide can be achieved through isolux curves or illuminance profiles in vertical sections of the room. Illuminance profiles give immediate information on the lighting level performed at a certain distance from the lightguide.

The problem is that an illuminance profile depends on the characteristics of the particular room (the distance between floor and ceiling or the walls’ reflectances, for instance, play an important role in the way the incoming flux is distributed). This means that profiles obtained with certain conditions cannot be validated for any case, while the candlepower distributions are totally independent from the room characteristics and are just specific for a lightguide with a certain aspect ratio under a certain type of sky.

Illuminance profiles are mostly influenced by two parameters: the height of the ceiling above the floor and the walls’ reflectances.

Simulations carried out by Bouchet and Fontoynont showed that variations of 0.3 of the walls’ reflectances caused a diminution of the daylight factor of only about 0.5% (Bouchet and Fontoynont, 1996). The distance between ceiling and floor (from now on “\( u \)”), on the other side, influences significantly the illuminance profile, both on quantity (lux level) and quality (shape of the profile).

Thus, measuring with a single building model implies fixing the proportions between distance \( u \), theunnel length and the dimensions of its section. Comparing lightguides with different section area would mean having several lightguide or building models, realized with different scale factors (changing the scale of the building while keeping the same lightguide has the same effect of creating a new virtual lightguide). Both solutions (especially the realization of many lightguides’ collectors) would increase the cost and the time needed for the experiments in an inappropriate way.

The problem was simplified by focusing only on the cases of very large spaces, where walls have no influence on the internally reflected component of the daylight factor.

Once border effects are considered negligible, only the floor and the ceiling are influencing the internal illuminance levels.

A building scale model was conceived based on this principle. A box of 1 x 1 x 0.5 [m] was built, with a hole and a lightguide support on the top (see fig. 5). Floor and ceiling surfaces have respectively reflectances equal to 0.30 and 0. Walls, on the contrary, are totally absorbing (black velvet with reflectance < 1%), accounting for this assumption.

\[ E(u) = \frac{I_k}{R} \]

\[ E_k = I_k \cdot \frac{1}{R} \]

where:

- \( I_k \) is the intensity emitted from the exit hole in the direction relative of the luxmeter \( k \).
- \( E_k \) is the illuminance [lux] measured by the \( k \)-th sensor.
- \( R \) is the circle radius (i.e. the distance from the hole, constant for all the sensors).

Figure 5. Schema of the building model with variable scale factor. This device was used to get illuminance profiles and to set up the abaci presented.

Nine sensors (illuminance-meters) are positioned on the floor, and since this latter is mobile, distance \( u \) can be varied arbitrarily without changing the building model.

Since sensors have to measure a DF, they are not put directly on the floor but lifted at a certain distance from it (depending on the actual scale of the building), corresponding to a 60 cm height in the reality.

By changing the distance between the sensors, while moving the box floor (i.e. changing the distance \( u \)), several configurations of lightguides can be measured.

6. EXPERIMENTAL RESULTS

Several configurations were analyzed under the scanning sky simulator, leading to many experimental results. The most significant ones are given here for different sky conditions.

6.1 CIE Overcast sky

Illuminance profiles show that lightguides equipped with anidolic collectors have performances slightly lower than plain devices (the total flux is roughly reduced by 20%). This is coherent as for strongly overcast conditions daylight is mostly diffuse, collectors reducing the entering flux though their mask effect.

Profiles obtained for CIE Overcast skies have typical features, with a single peak, corresponding to the sensor positioned exactly under the funnel axis (point E), and illuminance levels

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2 All comparisons concern a bidimensional case: illuminance profiles refer to the North-South axis.
rapidly decreasing as soon as the distance from point E increases (see fig. 6).

In absence of external collector, the profiles are perfectly symmetrical, since both the sky luminance distribution and the pipe geometry are symmetrical. A symmetry is recognizable also for lightguides with collectors: this is also normal since a CIE Overcast Sky provides a pretty uniform (if compared to a CIE Clear Sky) light distribution and perfectly uniform light distributions are transmitted by CPCs on the exit plane, showing lambertian features.

CIE Overcast Sky experiments show that the presence of an anidolic collector over the zenithal lightguide is acceptable for overcast conditions, the daylight factor being reduced however from 3.5% to 2.2% underneath the device (on the system axis).

6.2 CIE Clear Sky

The significant improvement of illuminances, due to the external anidolic collector, is illustrated in fig. 7. At summer solstice (at noon), the total flux is four times larger, compared to a lightguide without external device. Not only peak levels are increased (illuminance ratio of 29 % instead of 15 %), but also the average illuminance is highly improved: under the zenithal lightguide, for example, the illuminance ratio grows from less then 1% up to 17%.

The anidolic collectors contribute to the improvement of the illuminance ratio even for the winter solstice (illuminance ratio moves from 2.2 % to 5.2); fig. 8 illustrates this.

A second observation can be made when comparing with overcast profiles: for clear sky, illuminance has two or more peaks placed on both sides of the lightguide. The explication is easy if we consider the simplified case of a square pipe with the sun set on its axis: the problem is then bidimensional. Light is entering from a punctual source (the sun) so that rays are all coming from a punctual source (the sun) so that rays are all incident with the same inclination (that is the solar height). The entering light flux is split in two parts and, after several reflections, reaches the floor in two different areas, creating two different light spots, at each side of the lightguide.

The central point placed on the axis of the funnel gets now less daylight than the rest; the main contribution for it being the zenith, which shows lower luminances for clear sky conditions.

6.3 Comparison of anidolic collectors

Illuminance profiles showed that more open collectors (2D or 3D but with acceptance sector of 15°-95°), offer preferable performances than those characterized by a narrow input sector (15°-67°). Even if peak values are sometimes lower (at winter solstice, f.i.), it must be emphasized that open collectors...
increase illuminances in a more uniform way. At noon of summer solstice, for example, peaks relative to 2D open and close collectors are almost equal, while the minimum illuminance ratio under the lightguide is 17% for the open and only 7% for the “closer” one. According to the theory, this should be even more evident for overcast conditions, even if in this case measures show only a very slight difference.

Figure 9. Stereographic projection of the sky seen from point E (i.e. under the pipe axis), through a simple circular pipe (h/u=1.2, a/u=1/5). Values in each zone represent the relative “partial daylight factor”, that is the influence of that zone on the DF of point E. Almost the totality of the light received by the point E comes from the zenith.

Figure 10. Stereographic projection of the sky seen from point E (i.e. under the pipe axis), through a square lightguide (h/u=1.2, a/u=1/5), with an anidolic collector 2D, series 15°-95°. A 3D collector allows the point E to get light from more zones than the 2D and also spread around the N-S axis.

7. PRACTICAL DESIGN METHOD

Even if the only way to assess in an accurate way illuminance levels for lightguides implemented on a particular room is using the corresponding candlepower distribution under the funnel, it appears in practice that only very few architects or building engineers have the skills needed to use the corresponding lighting simulation software. More, this degree of precision would be useless in a phase where many building design parameters are still vague.

It is exactly in this moment, however, when the design of a lightguide should be considered, in order to avoid farther interferences with the building structure or with the technical equipment.

Schematically, only two important characteristics of the room must be known in the first part of the project to achieve this design:

1) $u$ (distance floor-ceiling);
2) $l$ (length of the funnel).

The distance of the ceiling from the floor, in fact, depends on the typology and regulation giving precise constraints, while the length of the lightguide is generally determined by the morphology of the site.

Data needed, on the other side, are:

1) the area of the pipe’s section ($A$);
2) the distance between lightguides ($D$);
3) the illuminance requirements.

These three parameters are sufficient to have a rough idea of the cost of the installation and of the lighting contribution of the lightguide ($D$ is directly related to the number of lightguides).

Distance $D$ is chosen first, starting from the illuminance profiles, depending on the required level and on the degree of uniformity desired.
Since only $u$ and $l$ values are available at the beginning, abacuses are labeled with $lu$ and provide profiles relative to devices with different $A$ ($l$ is constant, so the aspect ratio is varying). Thus, a certain lightguide can be chosen and $D$ is calculated.

7.1 Example of application

We just restrict our example to a bidimensional situation, neglecting the dimension on the East-West direction. The aim is to illuminate a subway station with the following characteristics:

$l=3\text{m}$; $u=2.5\text{ m}$; $L=9\text{ m}$, where $L$ is the depth of the unit considered (on the North-South direction).

A minimum DF of 1% is required$^3$ for the most penalized case (CIE Overcast Sky).

The ratio $lu$ is equal to 1.2, leading us to the corresponding abacus, relative to a CIE Overcast Sky.

The following lightguide could be chosen as a base case, defining a corresponding illuminance profile: $l = u/3.3$, collector CPC 2D 15° - 95°.

Once an illuminance profile is determined, $D$ can be calculated: it is the distance from the funnel axis, which corresponds to a DF of 0.5% (since we require a minimum daylight factor of 1% and two different lightguides sum their effects). $D \equiv u = 2.5\text{ [m]}$ is obtained in this case.

In conclusion, we have considered a system of lightguides with $l = 0.75\text{ m}$ (i.e. 2 lightguides on the 9 m depth), and spaced with a step of 5 m (i.e. 2$D$).

In order to estimate the daylighting autonomy of such a system, a simulation during a whole year was made under the scanning sky simulator, using the meteorological data relative to Geneva for 1994. Assuming working hours from 9 a.m. to 5 p.m., the autonomy of the lightguides was calculated, considering different comfort setpoints (see table 2).

The results reported in the figure show that if 100 lux are required for underground passages, a good autonomy is considered (on the North-South direction). The aim is to reach the following daylighting conditions (the flux is four times larger, at summer solstice, noon time). This corresponds to an excellent compromise for a fixed device.

Simple and ready-to-use abacuses were finally provided to the practitioners, in order to support the design of lightguides integrated in buildings.

Lightguides are shown to be efficient devices for introducing natural daylight into buildings. They are not intended to be substitutive but complementary to artificial lighting. Their benefit, apart from energy savings, concerns an increased visual comfort, both under a physiological and a psychological point of view.

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$^3$ For a very cloudy winter day the external illuminance is of about 10000 [lux]. Assuming 100 [lux] a sufficient illuminance for a subway station, we calculate the least favorable (i.e. the highest) daylight factor required as the ratio of these two illuminances (0.01).


