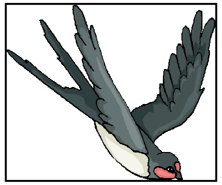
5th Forum on New Materials, Materials Solutions for Sustainable Energy, Montecatini Terme (PT), June 13-18, 2010



Optical Methods for Indoor Characterization of Small Size Solar Concentrators

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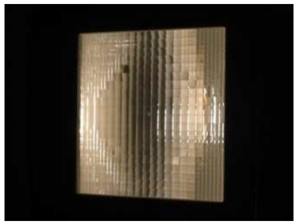
[2]Università di Ferrara, Dipartimento di Fisica, Ferrara, Italy
[3]CPower srl, Ferrara, Italy.




Reverse the sight of your world
You will get surprises!

SUMMARY

Short introduction to ***nonimaging*** solar concentrators

"**Direct methods**" of characterization of concentrators

i) The direct laser method (DLM)

ii) The direct collimated method (DCM)

iii) The direct integral method (DIM)

The "**Inverse method**" (IM) of characterization of concentrators

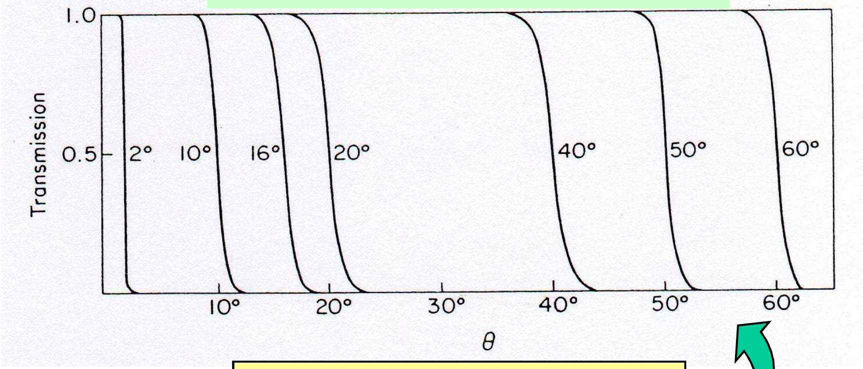
Applications

* Ideal 3D-CPCs
* Truncated and Squared CPCs
* Fresnel and prismatic lenses
* The "***Rondine***®" nonimaging PV concentrator

Conclusions

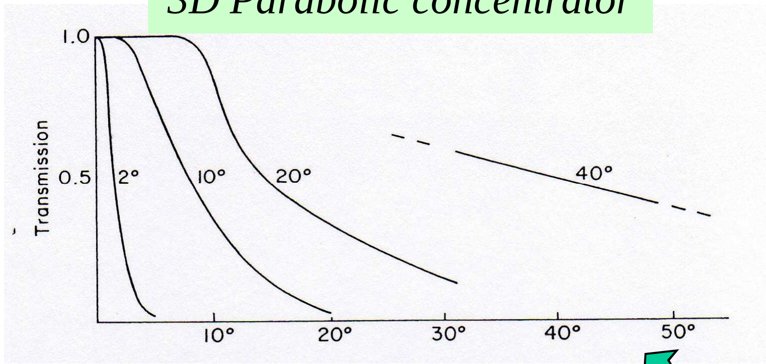
Optical efficiency curves of 3D-concentrators

3D-CPC Solar concentrator

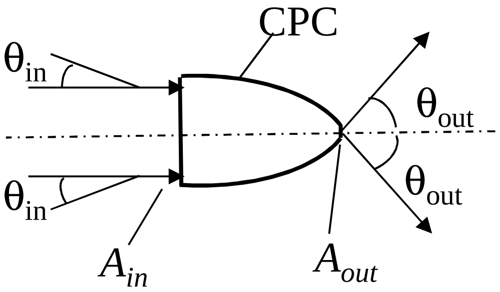


NONIMAGING

3D Parabolic concentrator

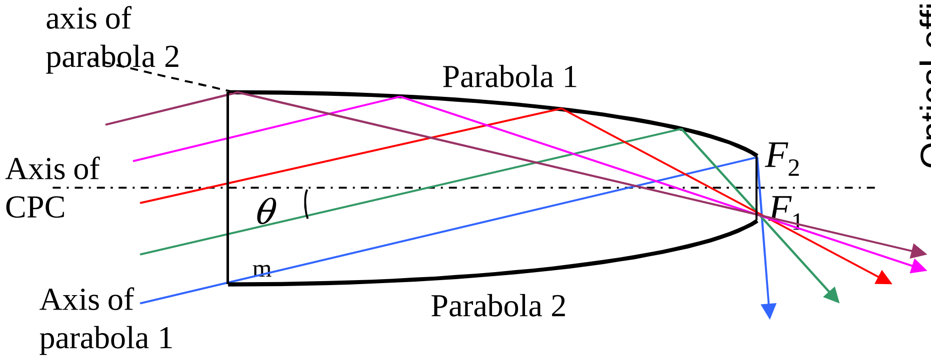


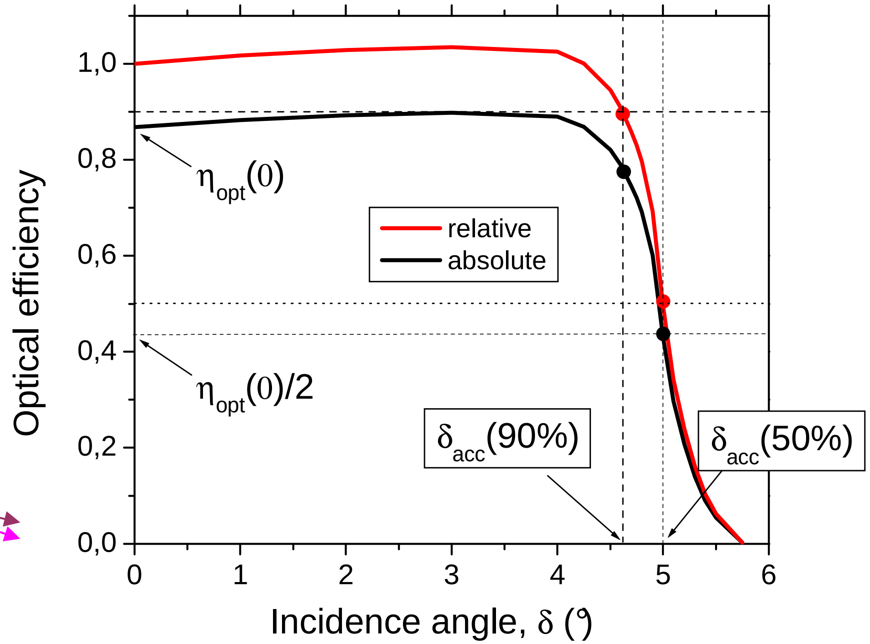
IMAGING



$$C_{opt} = \frac{\sin^2 \theta_{out}}{\sin^2 \theta_{in}}$$

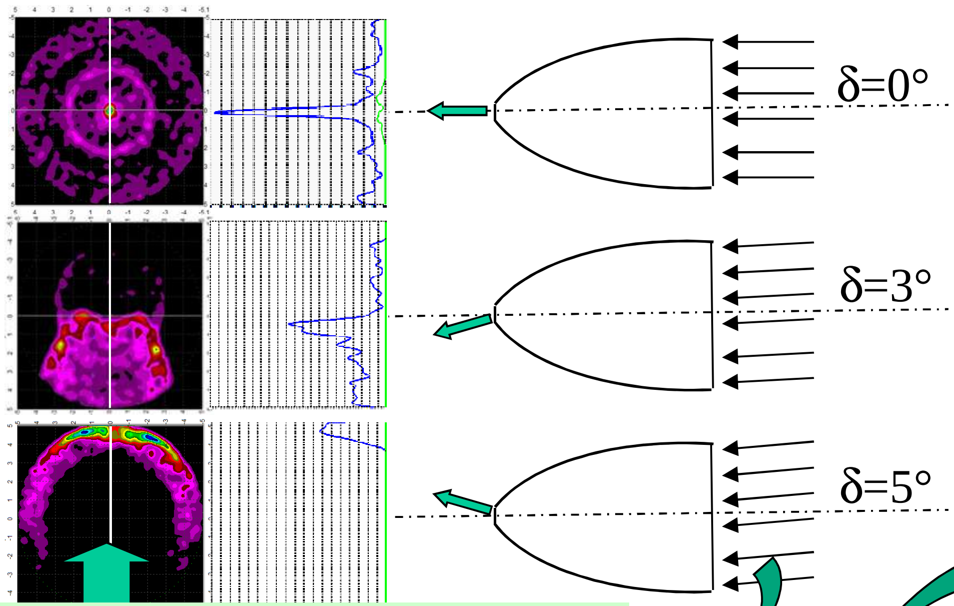
(in air)



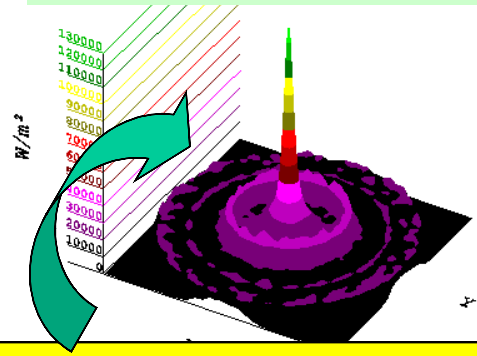


Absolute and relative transmission efficiency curves

The 3D Compound Parabolic Concentrator (3D-CPC)



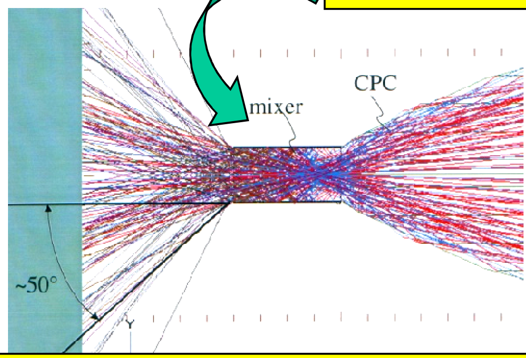
target illumination profile for normal irradiance

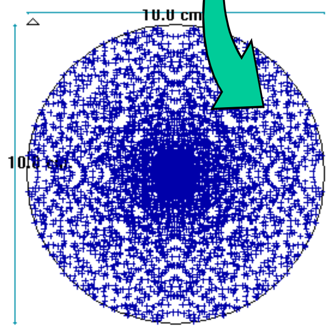


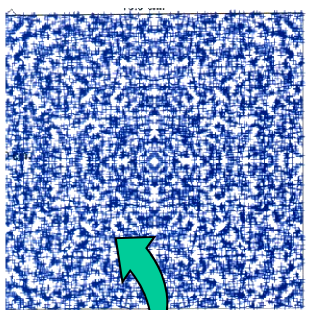
In general, we have a non uniform distribution of flux at output

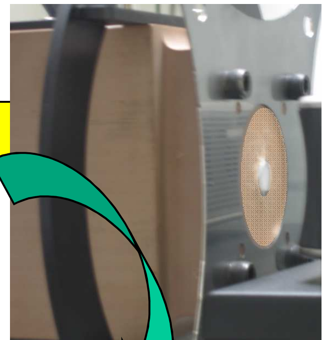
At δ=acceptance angle…the flux is on the rim of receiver

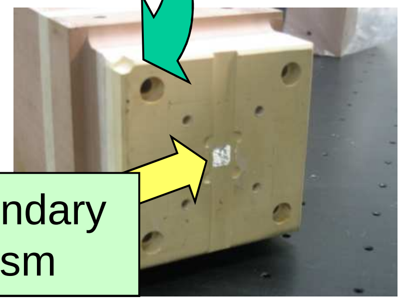
But the application of a secondary element…











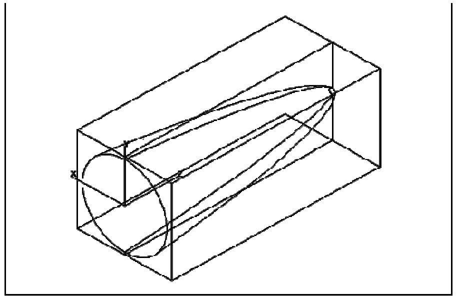
Secondary prism

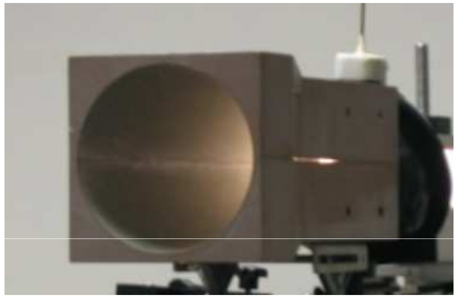
…allows to obtain a uniform flux at output

THE TESTED SOLAR CONCENTRATORS

The solar concentrators

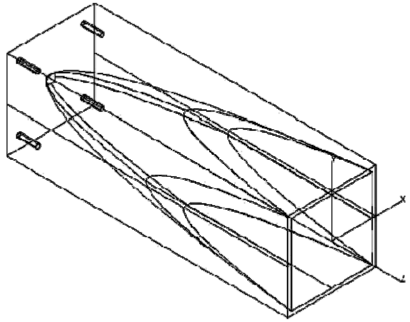
Nonimaging



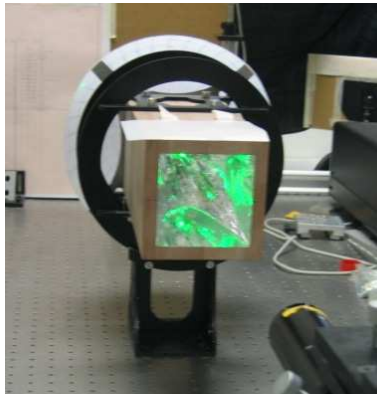


T-CPC
r(in) = 70 mm
r(out) = 5 mm
L = 350 mm

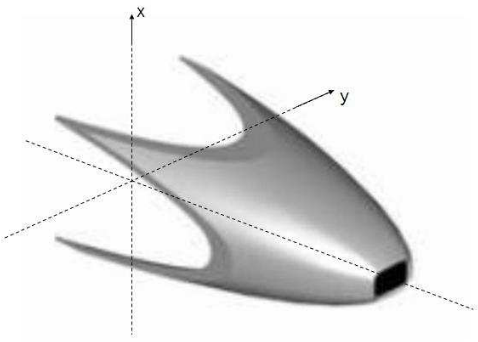
Truncated CPC (T-CPC)



TS-CPC
l(in) = 100 mm
r(out) = 5 mm
L = 350 mm



Truncated and Squared CPC (TS-CPC)



l(in)=6,7x6,7cm
l(out)=1,7x1,3cm
L=15cm
Axis Tilt=6°x4°

Rondine nonimaging Concentrator (Gen1)

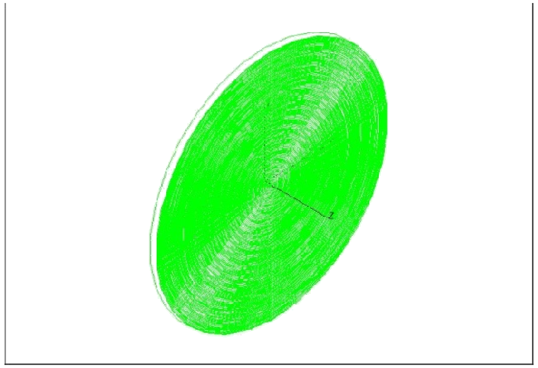
l(in)=3,5x3,5cm
l(out)=0,8x0,8cm
L=6.0cm
Axis Tilt=5°x5°

Rondine nonimaging Concentrator (Gen2)

The solar concentrators

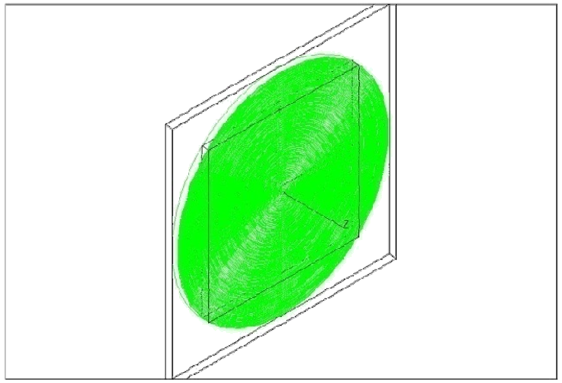
Imaging

- Fresnel lens (circular):



r=2,8cm
d=0,16cm

- Fresnel lens (squared):

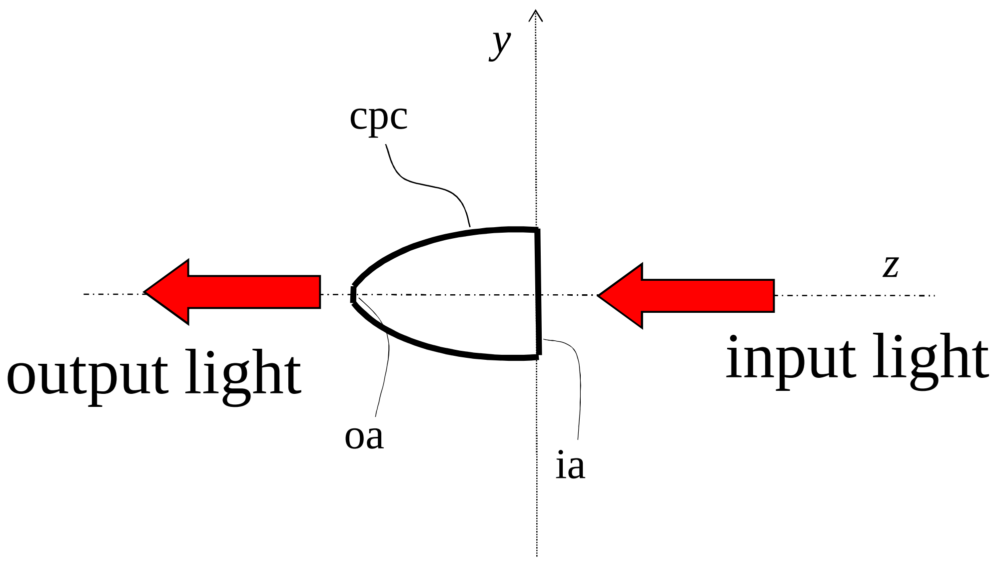


Mask 2x2cm

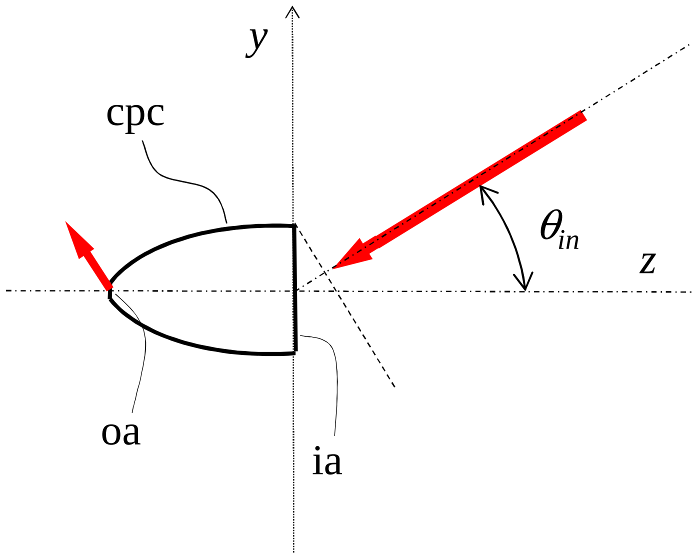
Prismatic lens Phocus concentrator

THE “DIRECT” METHODS

OF CHARACTERIZATION

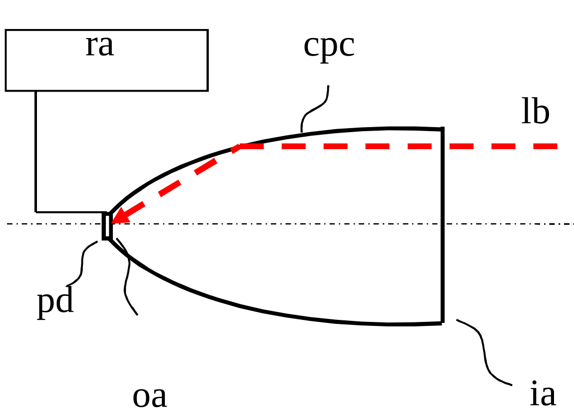


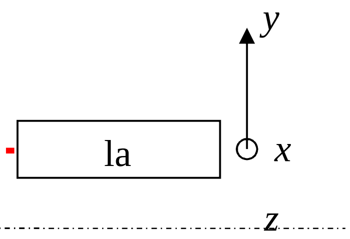
THE "DIRECT LASER METHOD" (DLM)

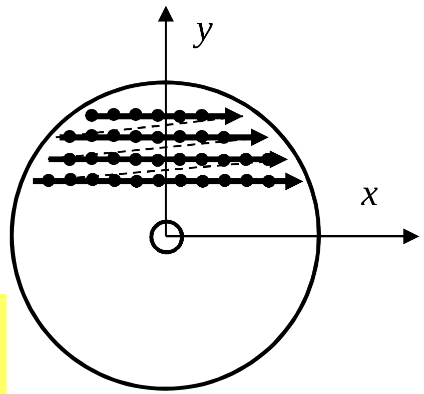


Local (directional) transmission efficiency

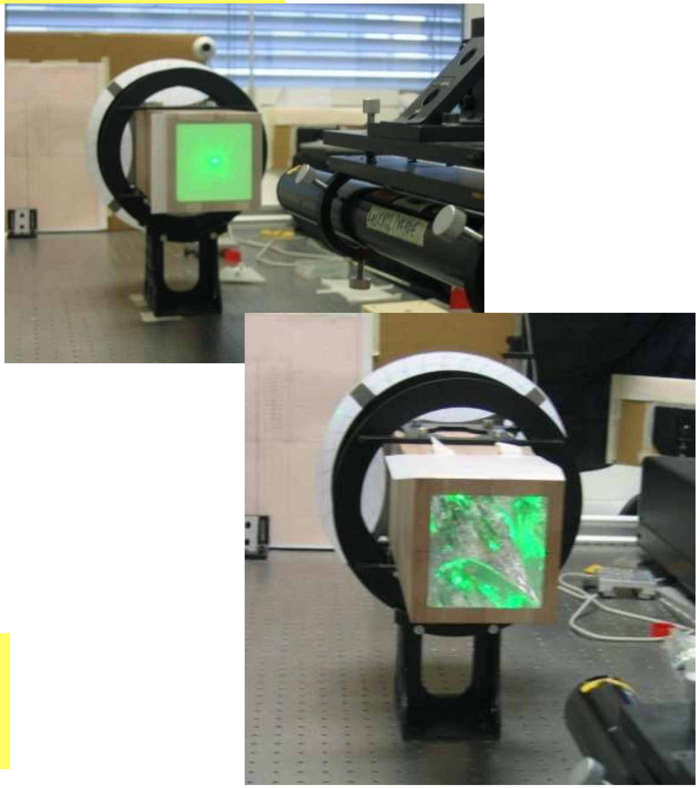
The laser method (LM)

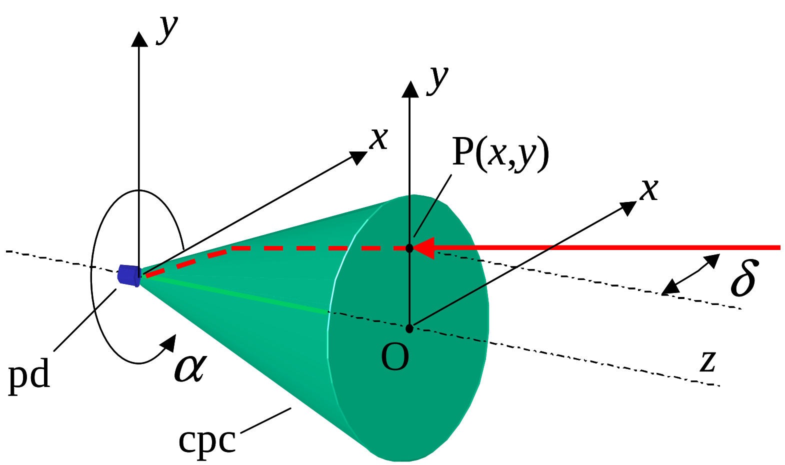






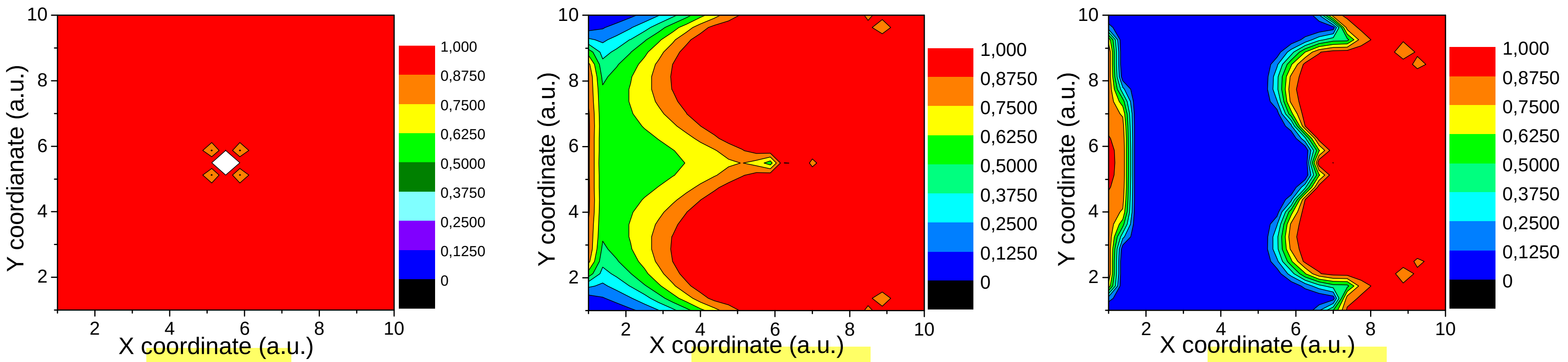
The laser beam is scanned over
a matrix path along x, y directions





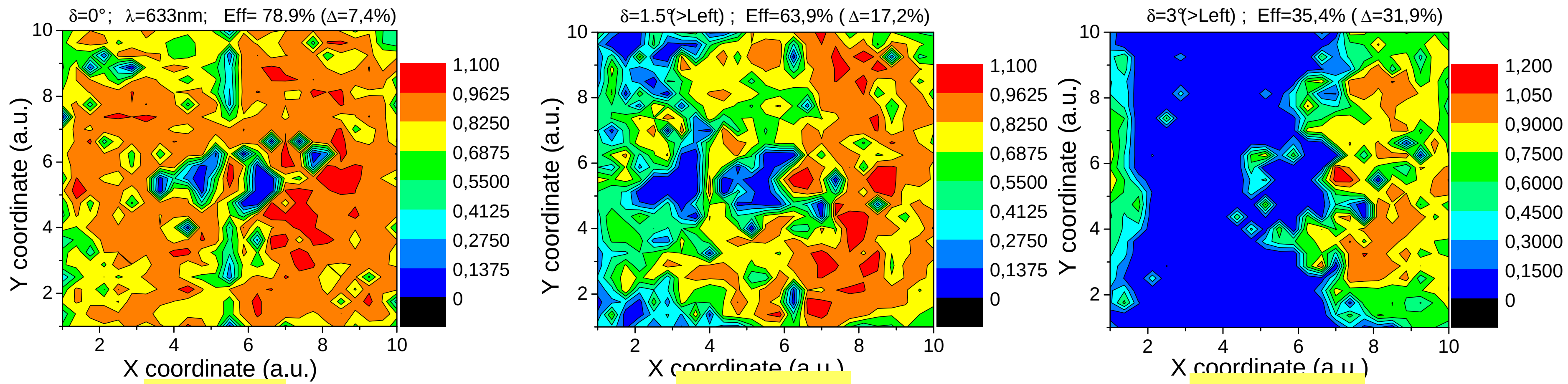
The laser beam is oriented at α (azimuth) and δ (polar) angles respect to CPC

Maps of optical efficiency (α = 0°)



$\delta = 0°$ $\delta = 1.5°$ $\delta = 2.5°$

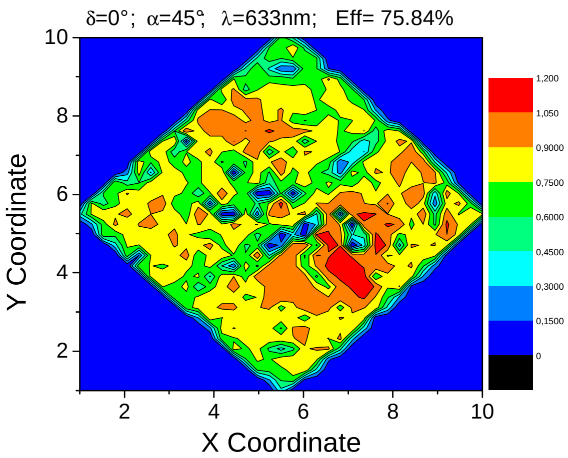
Simulated



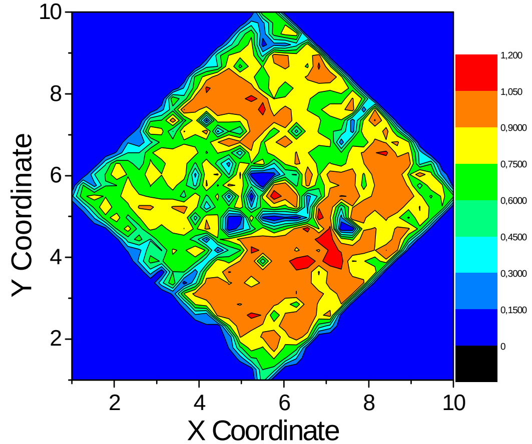
$\delta = 0°$ $\delta = 1.5°$ $\delta = 3.0°$

Experimental

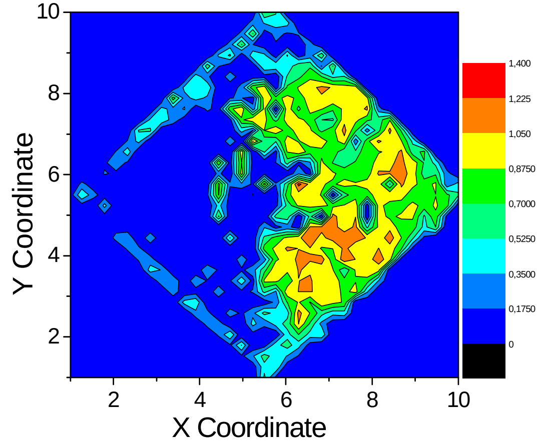
Maps of optical efficiency (α = 45°)



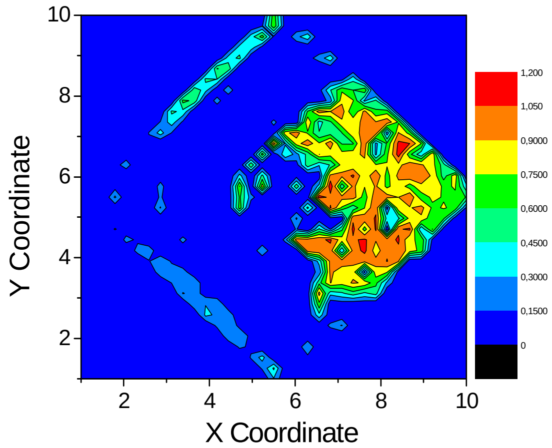
$\delta = 0°$



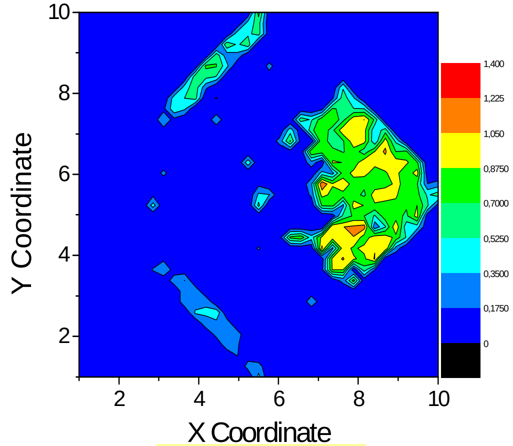
$\delta = 1.0°$



$\delta = 2.0°$



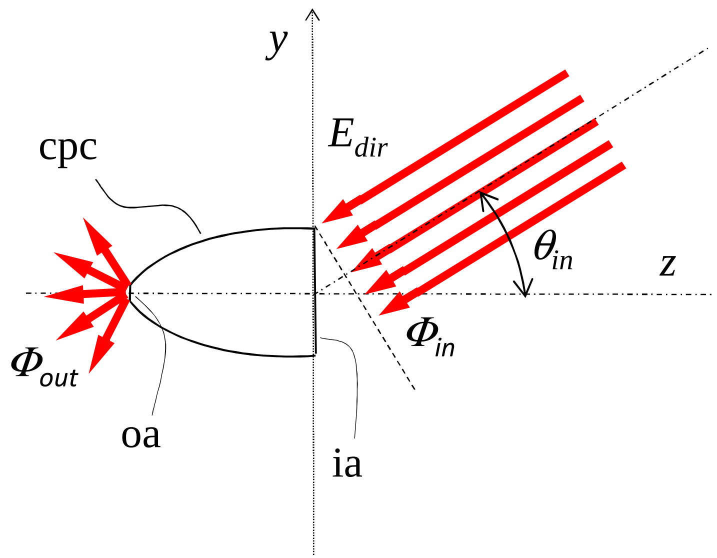
$\delta = 3.0°$



$\delta = 4.0°$

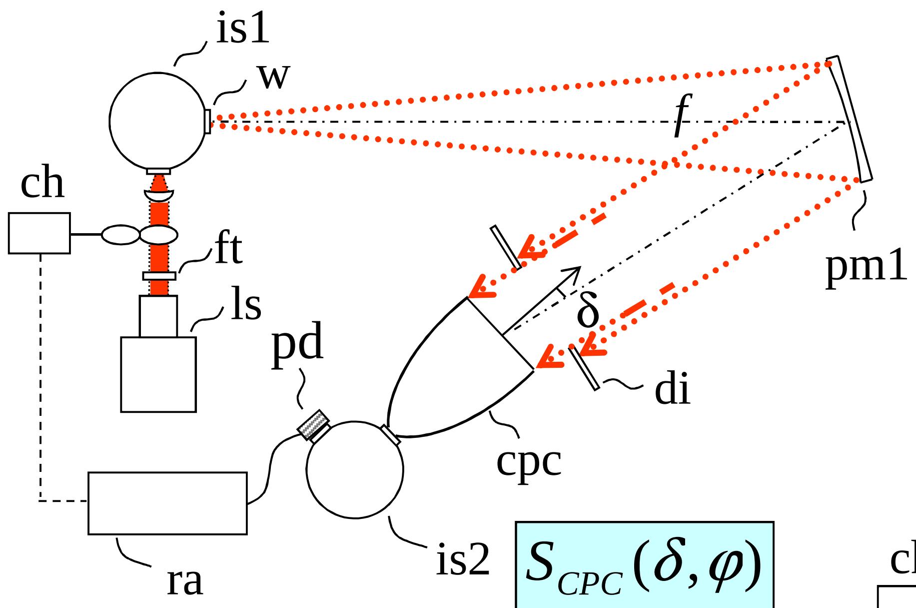
THE "DIRECT COLLIMATED METHOD" (DCM)

(The typical operation of a solar concentrator!)



Overall (directional) transmission efficiency

The experimental apparatus



$$S_{CPC}(\delta,\varphi)$$

Measurement of flux at output

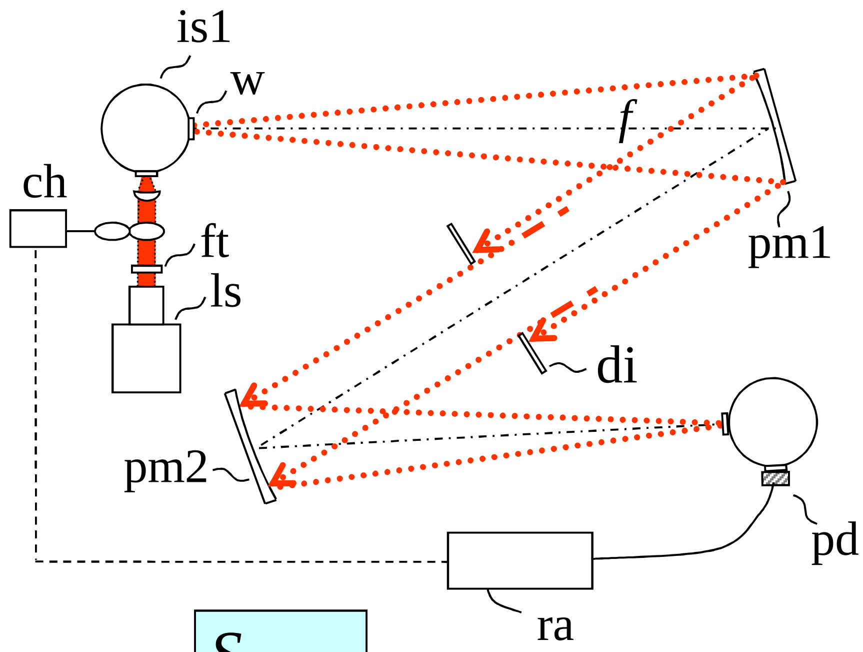
$$\eta(\delta,\varphi) = S_{CPC}(\delta,\varphi)\cdot\frac{R_{pm2}}{S_{REF}\cdot\cos\delta}$$

(Non-rotational symmetry)

$$\begin{cases}\delta = \text{polar angle}\\ \varphi = \text{azimuthal angle}\end{cases}$$

$$\eta(\delta) = S_{CPC}(\delta)\cdot\frac{R_{pm2}}{S_{REF}\cdot\cos\delta}$$

(Rotational symmetry)



$$S_{REF}$$

Measurement of flux at input

Experimental apparatus (Ferrara Labs)

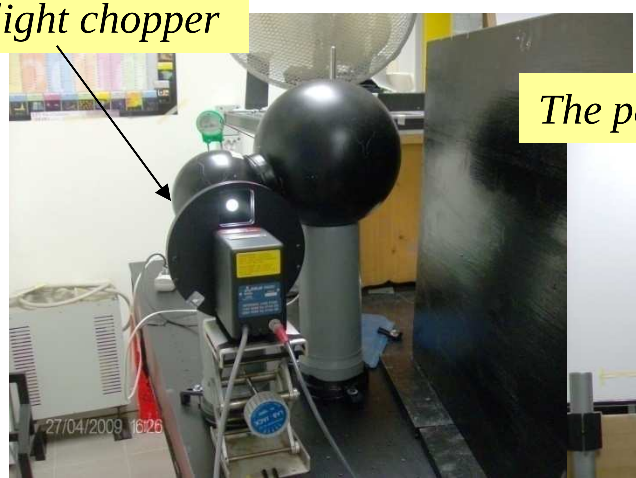
Characterization of "Rondine" nonimaging concentrator

The source: two coupled integrating spheres

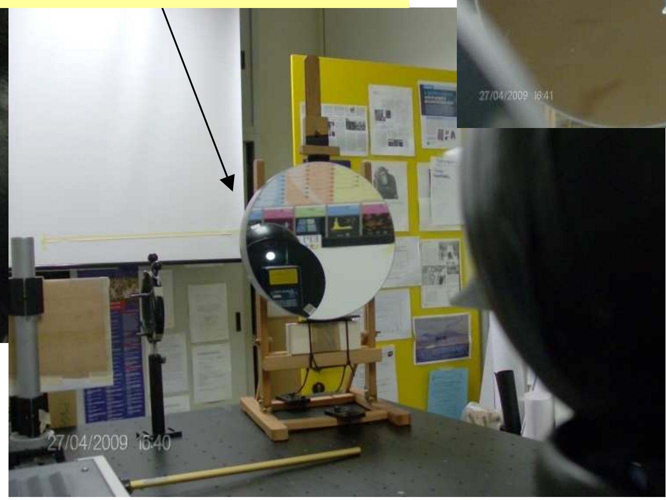
A fan is used to cool the spheres

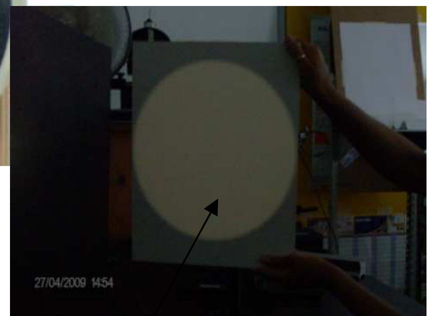
A lamp is placed inside the big sphere

The light chopper



The parabolic mirror

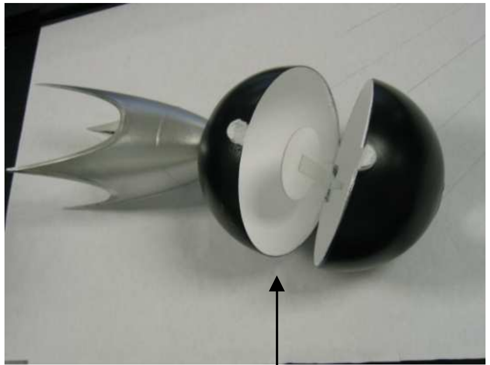




A uniform beam is produced

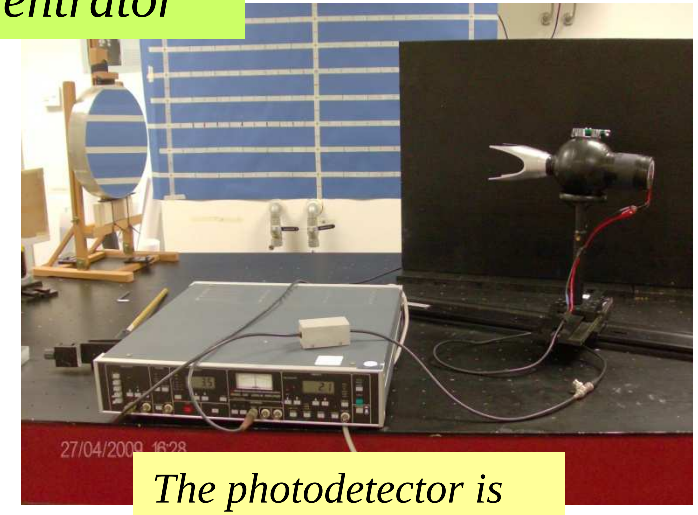
Experimental apparatus (Ferrara Labs)

Characterization of “Rondine” nonimaging concentrator

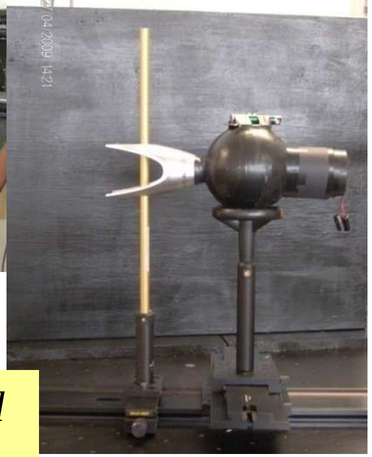


The Rondine is coupled to an integrating sphere

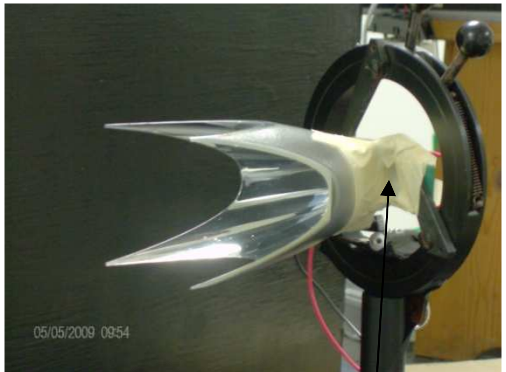
A photodetector is placed inside the integrating sphere



The photodetector is connected to a lock-in

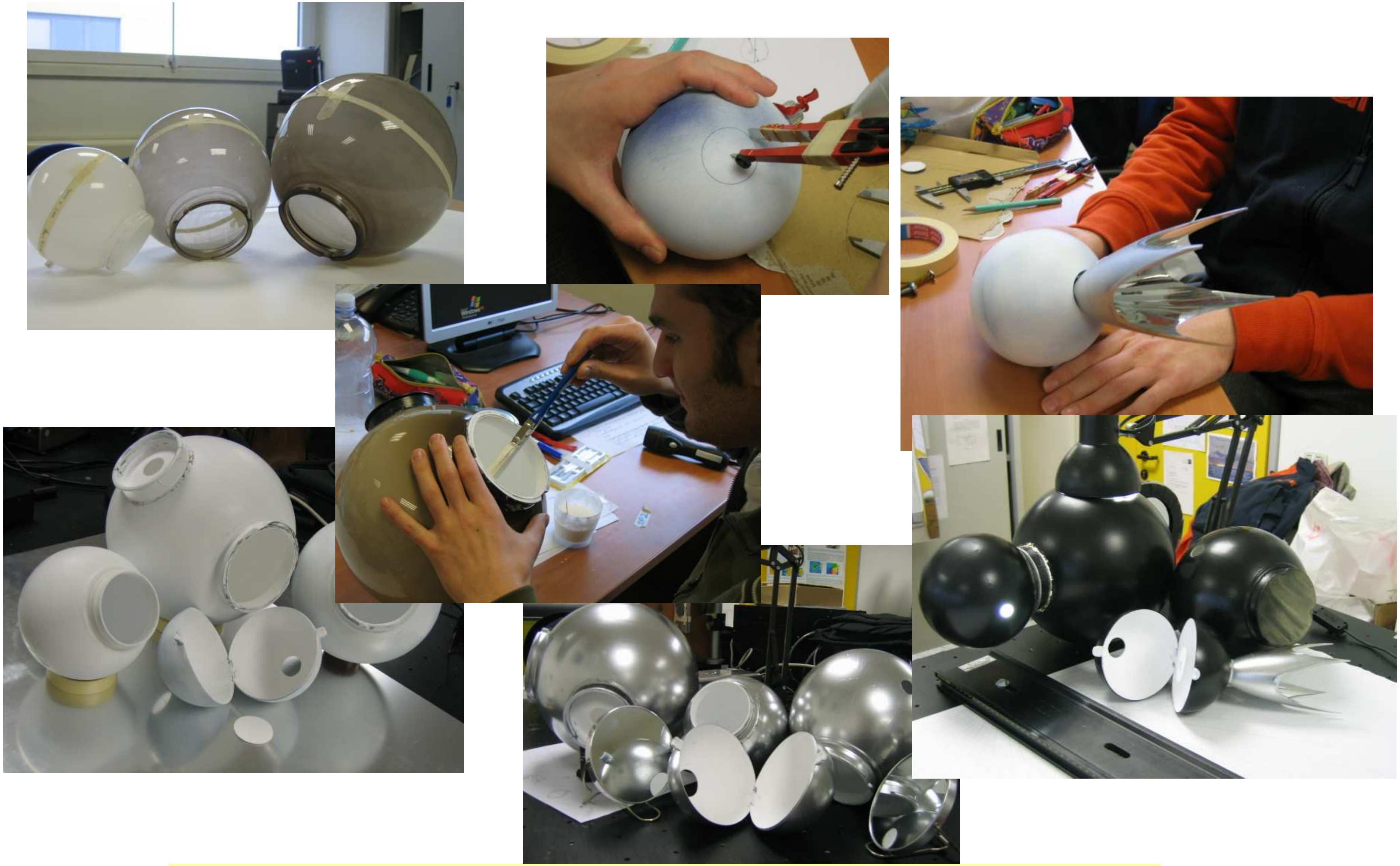


The Rondine is aligned respect to the beam



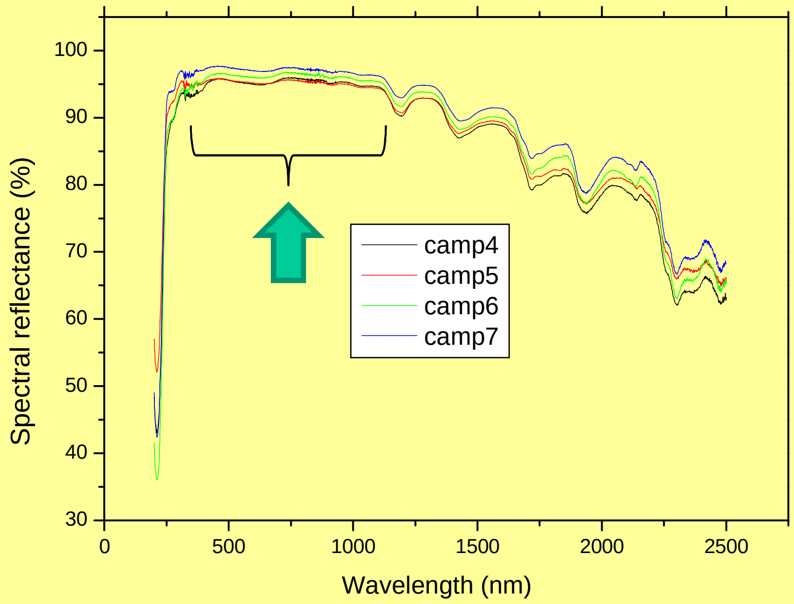
Here the Rondine concentrator is directly coupled to a solar cell

Realization of the integrating spheres (Ferrara Labs)



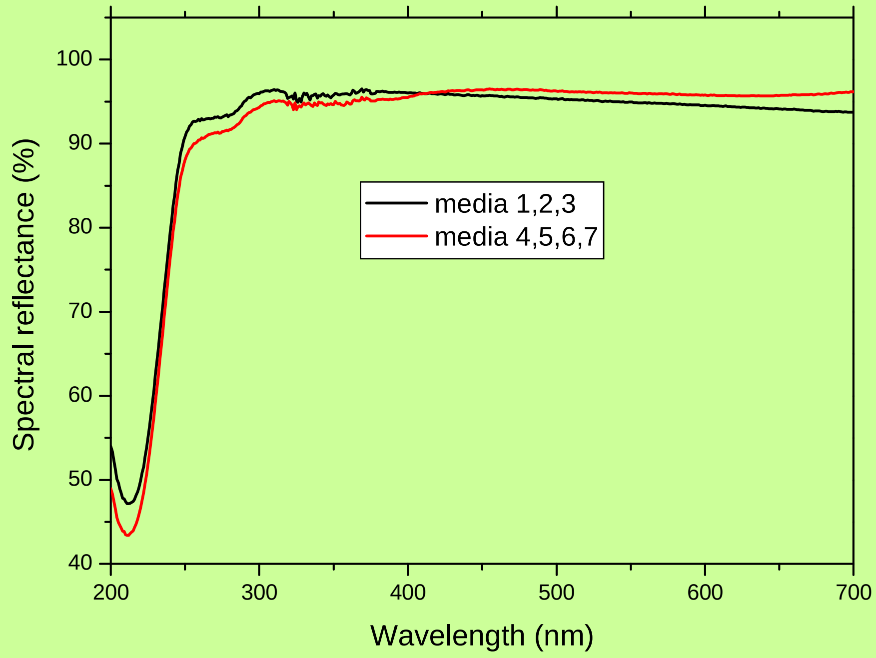
All the integrating spheres were realized from plastic globes by using different paintings.The internal wall was painted by Barium Sulfate.

Optical properties of the integrating spheres



Very good response at Vis-NIR!

Home-made BaSO4 coatings

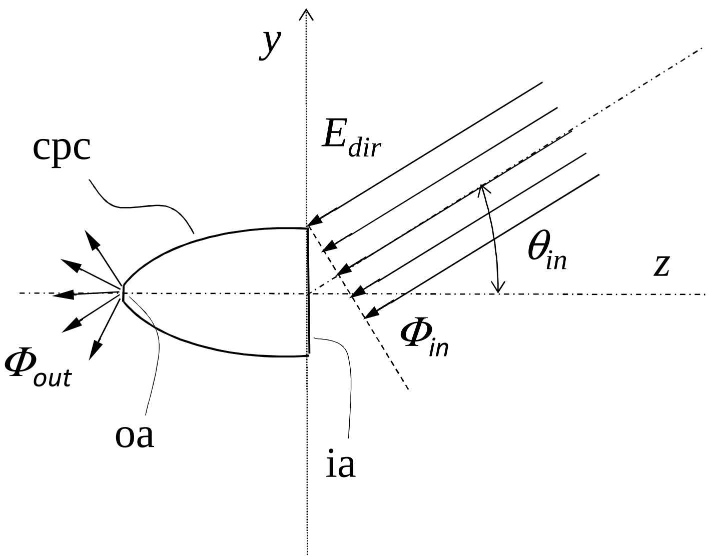


Excellent response at UV!

TRANSMISSION EFFICIENCY OF A SOLAR CONCENTRATOR
(Direct Collimated Method)

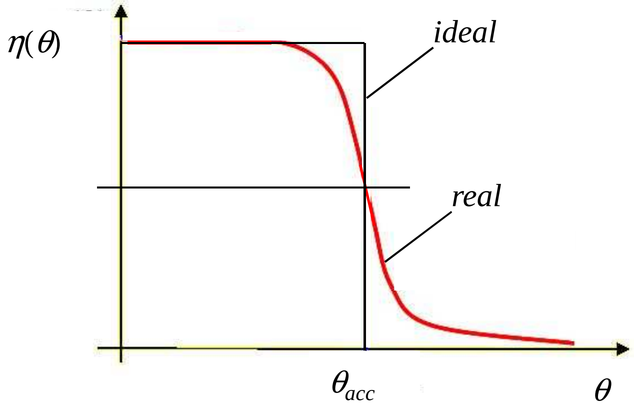
The fundamental quantity which summarizes the optical collection properties of a solar concentrator (SC) is the (angle-resolved) transmission efficiency:

$$\eta_{dir}(\theta_{in},\varphi_{in}) = \frac{\Phi_{out}(\theta_{in},\varphi_{in})}{\Phi_{in}(\theta_{in},\varphi_{in})} = \frac{\Phi_{out}(\theta_{in},\varphi_{in})}{E_{dir}\cdot A_{in}(\theta_{in},\varphi_{in})}$$



Schematic principle of Direct Collimated Method (DCM).

The SC is irradiated by a collimated beam oriented at θ_{in} zenithal angle, φ_{in} azimuthal angle.
E_{dir} : irradiance at the wavefront.
Φ_{in} : input flux.
Φ_{out} : output flux.
$A_{in}(\theta_{in}, \varphi_{in})$: projected input area.



Example of transmission efficiency curve of a 3D-CPC concentrator.

ANGLE-RESOLVED PROPERTIES OF A SOLAR CONCENTRATOR

In general we have:
Transmission efficiency: $\eta_{dir}(\theta_{in}, \varphi_{in})$ = fraction of transmitted flux:

$$\eta_{dir}(\theta_{in}, \varphi_{in}) = \frac{\Phi_{out}(\theta_{in}, \varphi_{in})}{\Phi_{in}(\theta_{in}, \varphi_{in})}$$

Absorption efficiency: $\alpha_{dir}(\theta_{in}, \varphi_{in})$ = fraction of absorbed flux:

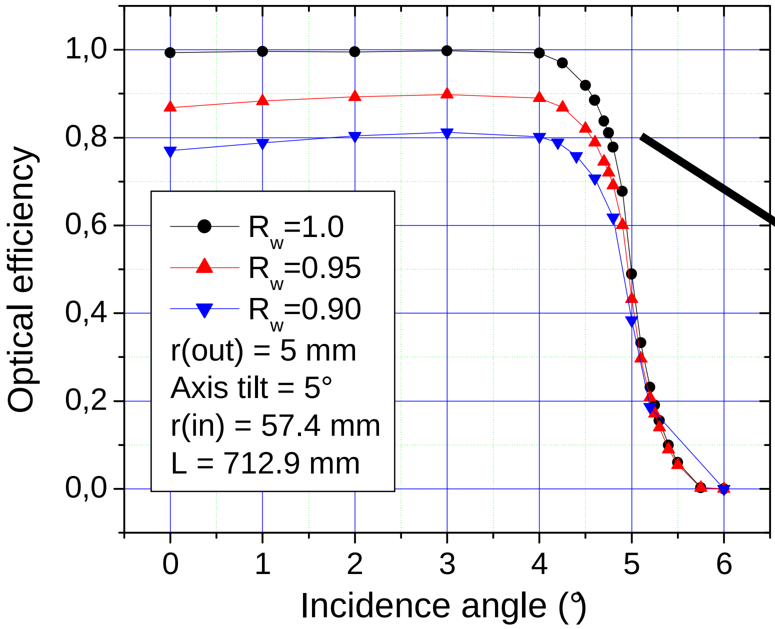
$$\alpha_{dir}(\theta_{in}, \varphi_{in}) = \frac{\Phi_{\alpha}(\theta_{in}, \varphi_{in})}{\Phi_{in}(\theta_{in}, \varphi_{in})}$$

Reflection efficiency: $\rho_{dir}(\theta_{in}, \varphi_{in})$ = fraction of reflected flux:

$$\rho_{dir}(\theta_{in}, \varphi_{in}) = \frac{\Phi_{\rho}(\theta_{in}, \varphi_{in})}{\Phi_{in}(\theta_{in}, \varphi_{in})}$$

with: $$\eta_{dir}(\theta_{in}, \varphi_{in}) + \alpha_{dir}(\theta_{in}, \varphi_{in}) + \rho_{dir}(\theta_{in}, \varphi_{in}) = 1$$

Optical simulations of 3D-CPC with DCM

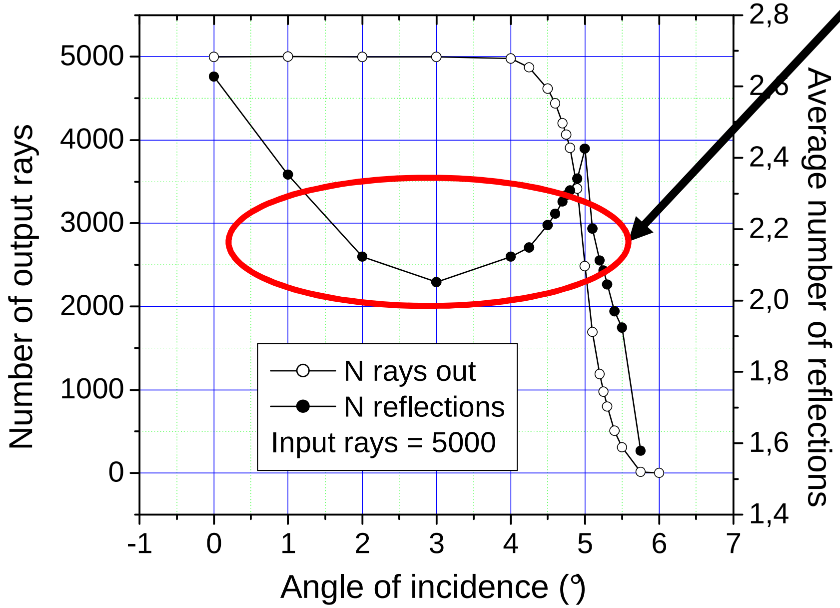


3D-CPC concentrator of 1-cm output diameter and 5°-axis tilt

Efficiency loss vs Reflectivity of the CPC walls:

$$-10\% \;\; R_W \rightarrow -20\% \;\; \eta(\theta)$$

Average number of reflections: ≈ 2:



$$R_w = 1.0 \quad \Rightarrow \quad \eta(\delta) = \Phi_{out}(\delta) / \Phi_{in}$$

$$R_w^{'} \quad \Rightarrow \quad \eta'(\delta) = \Phi_{out}^{'}(\delta) / \Phi_{in} = \Phi_{out}(\delta) \cdot (R_w^{'})^{\overline{N}(\delta)} / \Phi_{in}$$

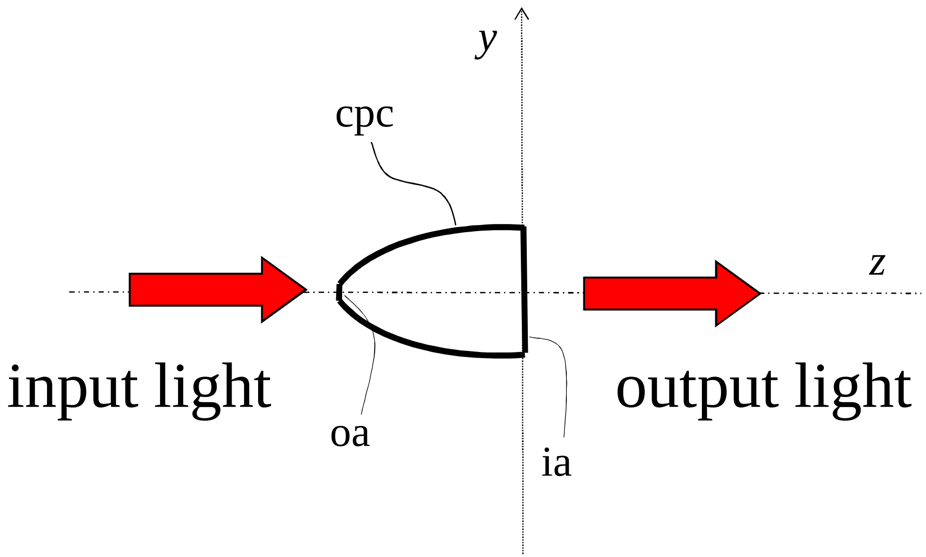
$$R_w^{''} \quad \Rightarrow \quad \eta''(\delta) = \Phi_{out}^{''}(\delta) / \Phi_{in} = \Phi_{out}(\delta) \cdot (R_w^{''})^{\overline{N}(\delta)} / \Phi_{in}$$

$$\overline{N}(\delta) = \ln\left[\frac{\eta'(\delta)}{\eta(\delta)}\right] \Bigg/ \ln\left[\frac{R_w^{'}}{R_w^{''}}\right]$$

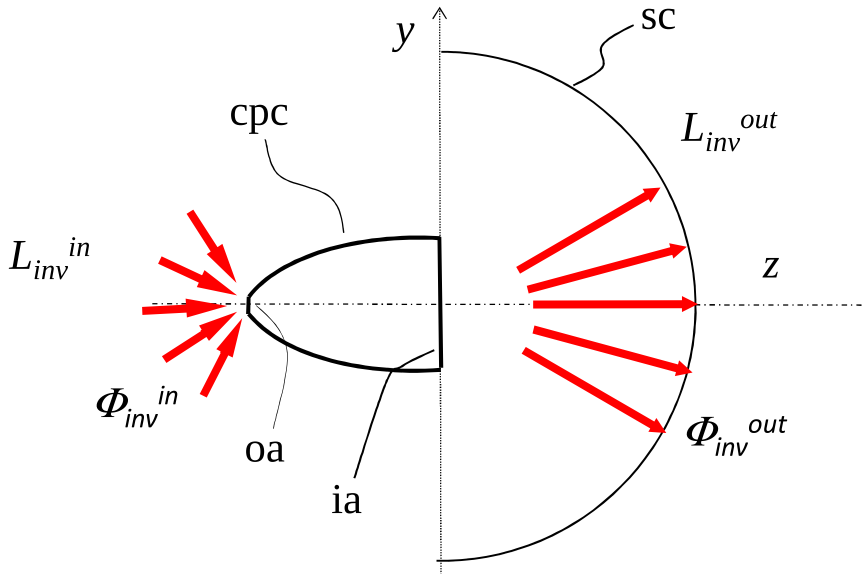
Average number of reflections From a pair of efficiency curves

THE “INVERSE” METHODS

OF CHARACTERIZATION



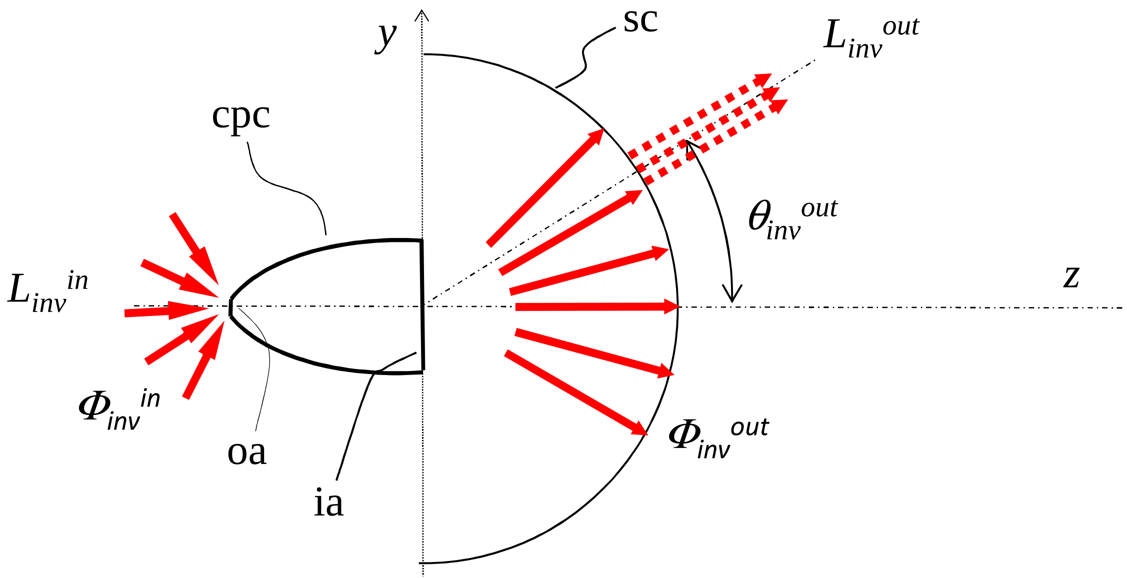
THE "INVERSE METHOD" (IM)
or
"ILLUME" (Inverse Illumination Method)



Overall (directional) transmission efficiency

We can demonstrate that:

The "inverse" emission efficiency (the radiance)



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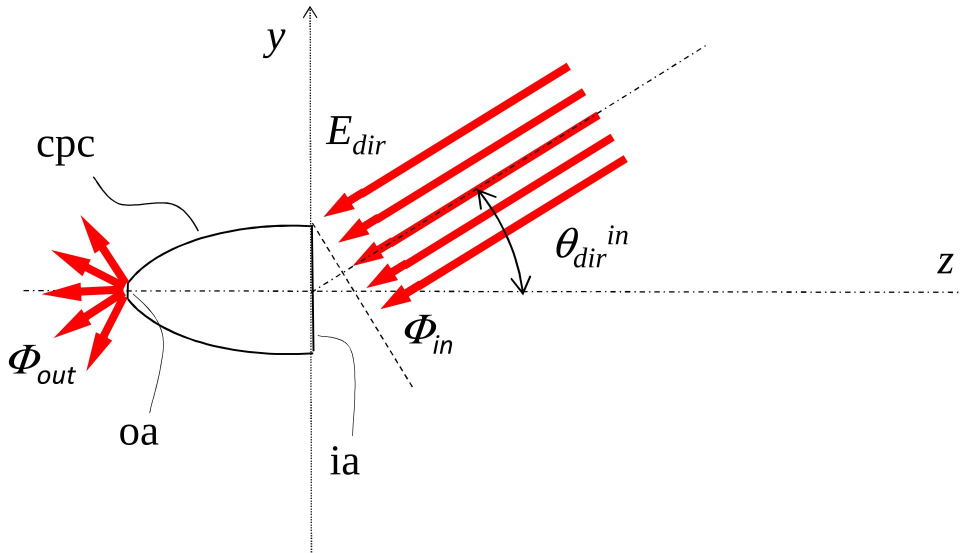
The "direct" collection (transmission) efficiency

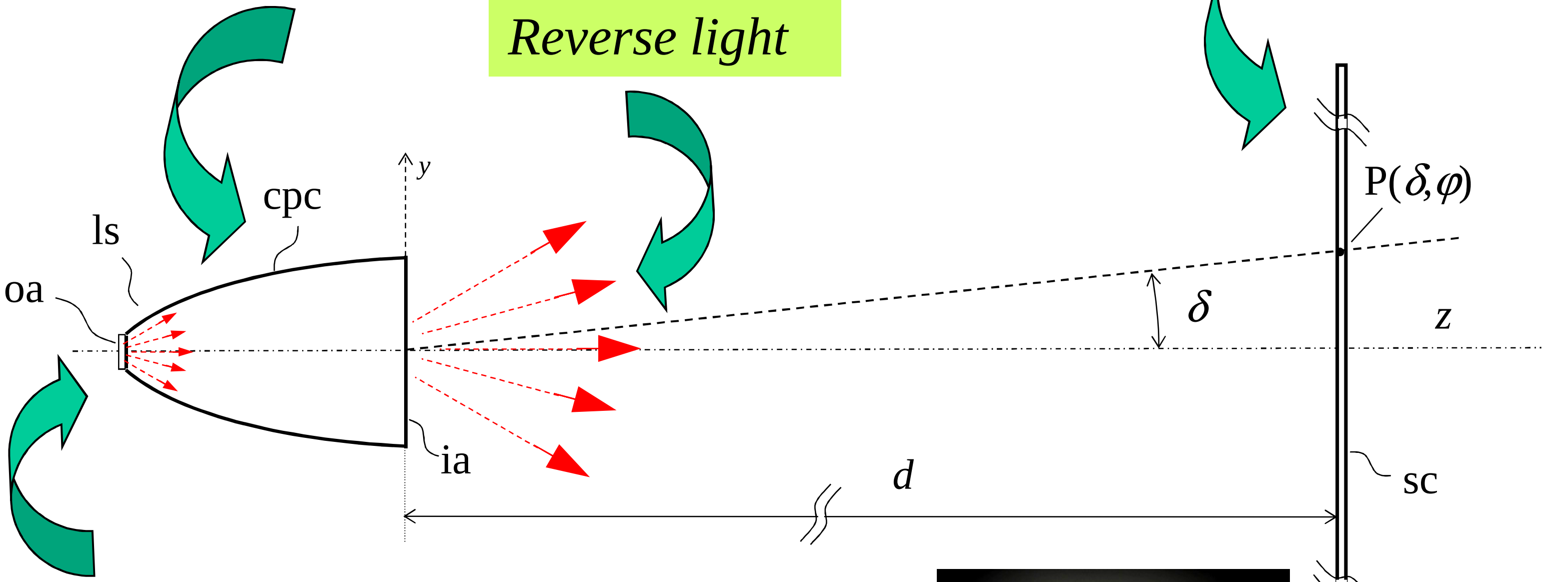


The basic principle of inverse method

The concentrator becomes a source of light!

A far Lambertian screen intercepts the reverse light

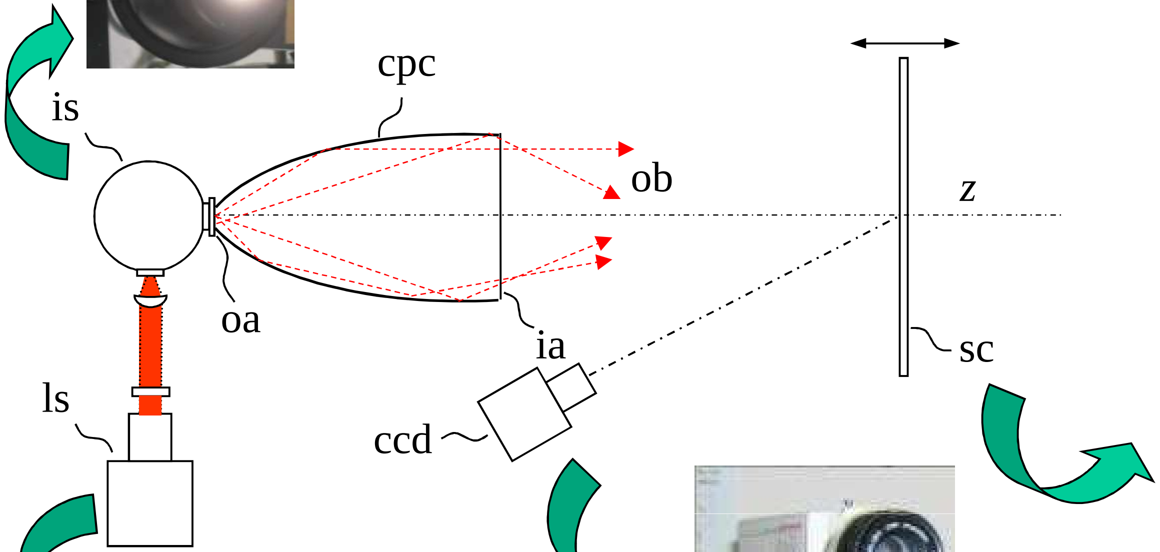
Reverse light

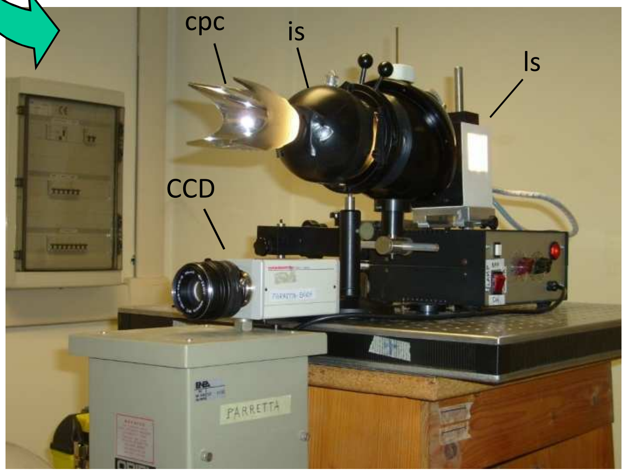


*A **LAMBERTIAN** source is applied to output aperture*

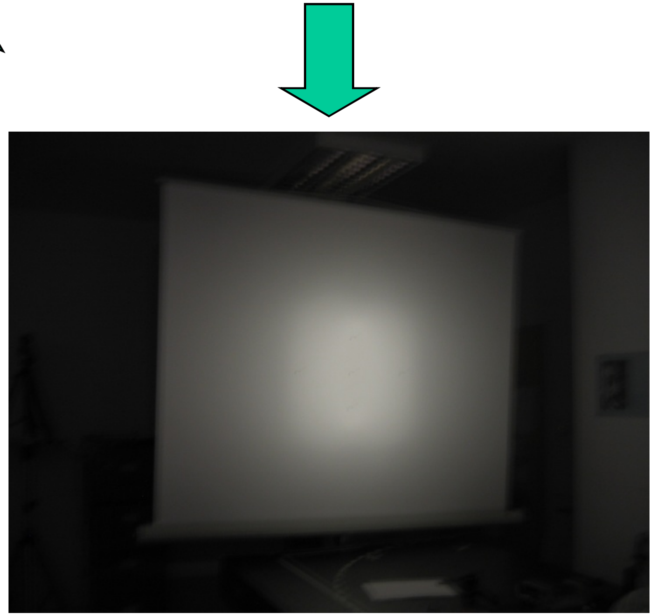
The image on the screen contains the <u>overall</u> information about the optical efficiency of concentrator

Experimental configurations





Hamamatsu C8484
CCD camera



Back illumination by an integrating sphere

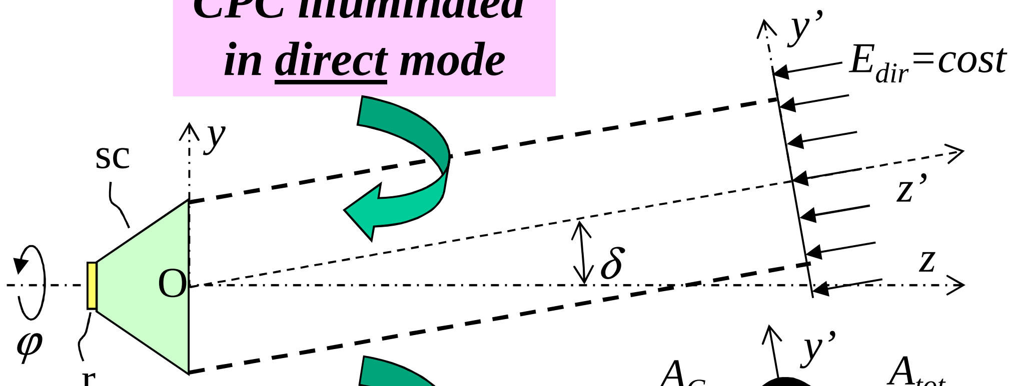
Simplified theory of ILLUME (Ideal concentrator)

$\Phi_{in}(\delta)$: flux at input

$\Phi_{out}(\delta,\varphi)$: flux at output

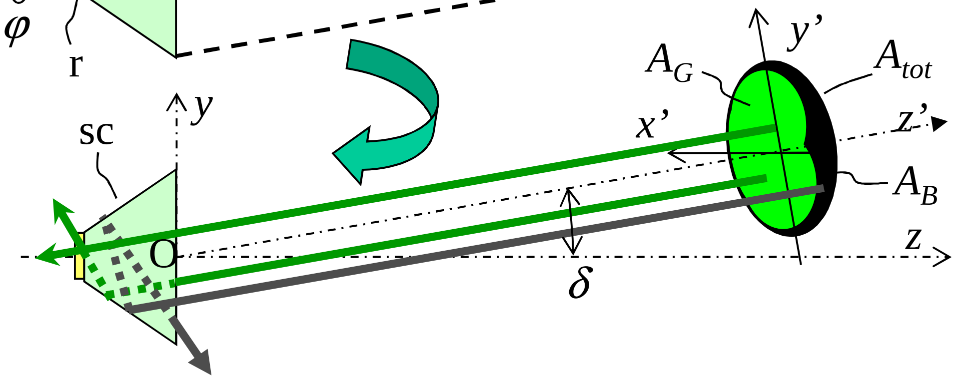
$$\eta(\delta,\varphi) = \Phi_{out}(\delta,\varphi) / \Phi_{in}(\delta)$$

CPC illuminated in <u>direct</u> mode



<u>Forward rays</u> at input are collected or rejected:

Collected flux ∝ to optical efficiency

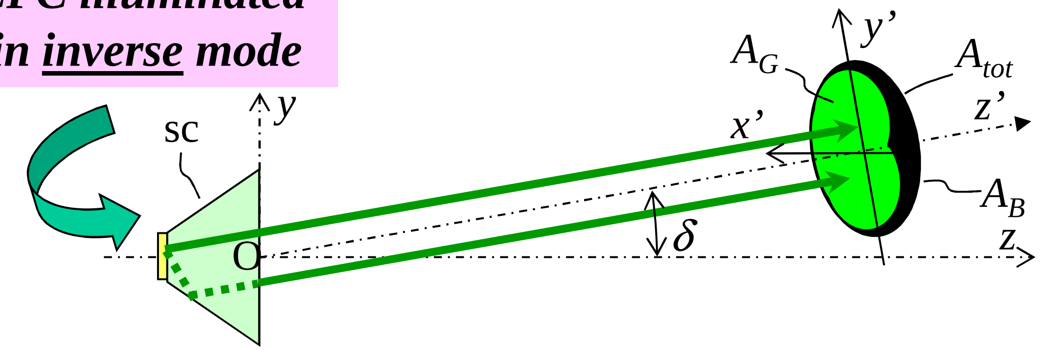


$$\eta(\delta,\varphi) = A_G(\delta,\varphi) / A_{tot}(\delta)$$

CPC illuminated in <u>inverse</u> mode

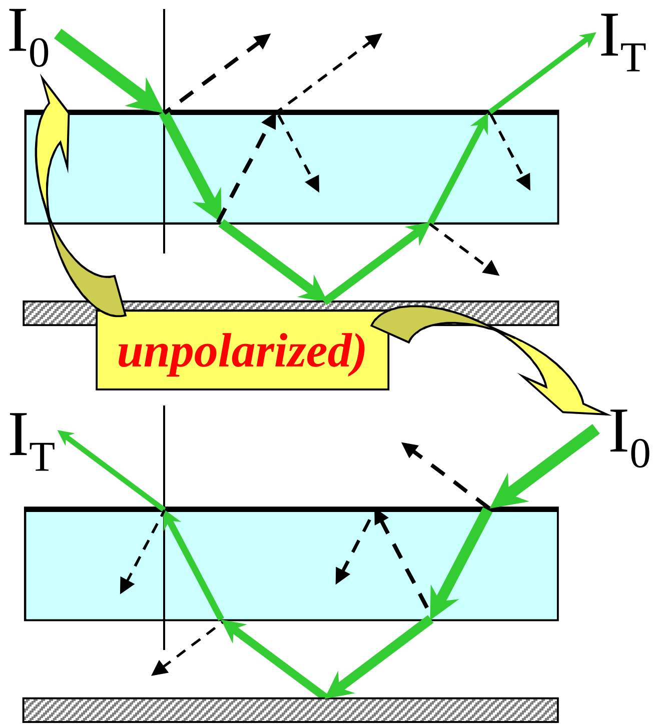
<u>Reverse rays</u> at output are always collected:

Emitted flux ∝ to reverse radiance



Reverse radiance ∝ to optical efficiency!!!

Simplified theory of ILLUME (Real concentrator)



Optical loss at interfaces inside the concentrator

For a real concentrator, we can apply the "reversibility principle" which establishes the same attenuation factor if the direction of light is reversed (and input light is unpolarized)

Reversibility Principle

I_T / I_0 =attenuation factor= invariant

For a single interface we can apply the Fresnel Equations:

(R and T are invariant for exchange between indexes)

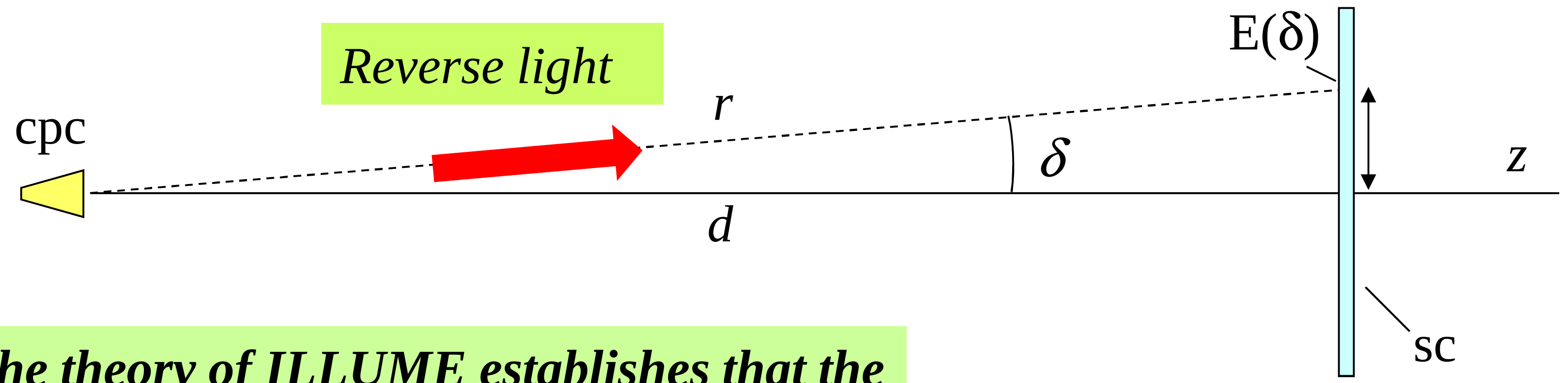
Attenuation of reflected ray

$$R = \frac{1}{2} \cdot \left(\rho_p^2 + \rho_s^2\right) = \frac{1}{2} \cdot \sin^2(\varphi - \varphi') \cdot \left[\frac{\cos^2(\varphi + \varphi') + \cos^2(\varphi - \varphi')}{\sin^2(\varphi + \varphi') \cdot \cos^2(\varphi - \varphi')}\right]$$

Attenuation of transmitted ray

$$T = \frac{1}{2} \cdot \left(\frac{n'}{n}\right) \cdot \left(\frac{\cos\varphi'}{\cos\varphi}\right) \cdot \left(\tau_p^2 + \tau_s^2\right) = 2 \cdot \sin\varphi \cdot \sin\varphi' \cdot \cos\varphi \cdot \cos\varphi' \cdot \left[\frac{1 + \cos^2(\varphi - \varphi')}{\sin^2(\varphi + \varphi') \cdot \cos^2(\varphi - \varphi')}\right]$$

Simplified theory of ILLUME



The theory of ILLUME establishes that the radiance of concentrator in the inverse mode is proportional to its transmission efficiency in direct mode!!

$$L_{rel}^{inv}(\delta,\varphi) = \eta_{rel}(\delta,\varphi)$$

How to calculate the radiance profile from the irradiance profile on the screen? Simply dividing by cos⁴(δ)

$$L_{inv}^{rel}(\delta,\varphi) = E_{inv}^{rel}(\delta,\varphi) \cdot \frac{1}{\cos^4 \delta}$$

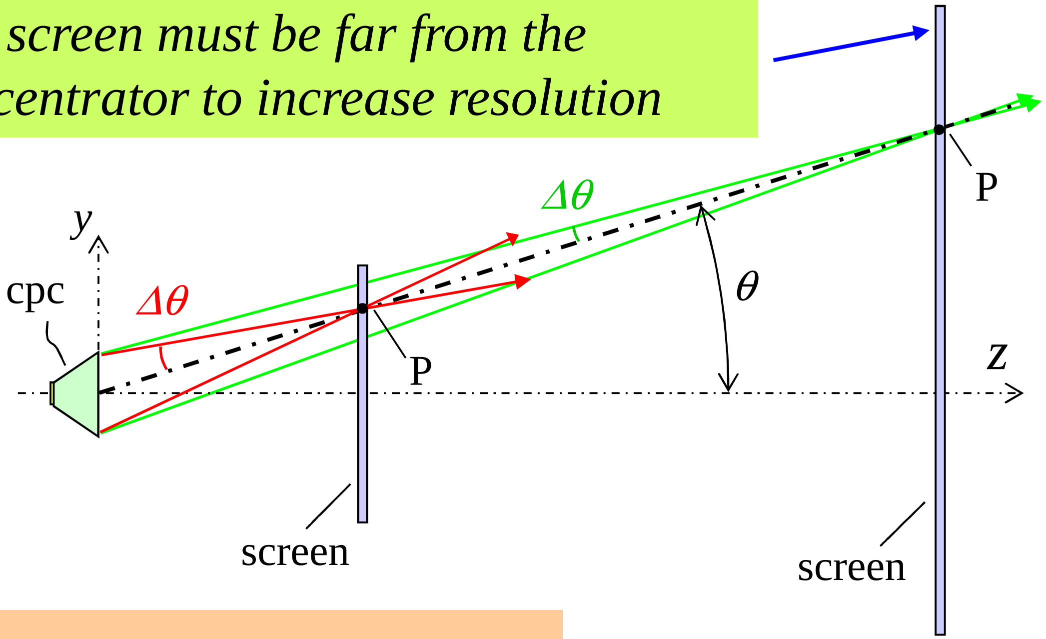
General formula:

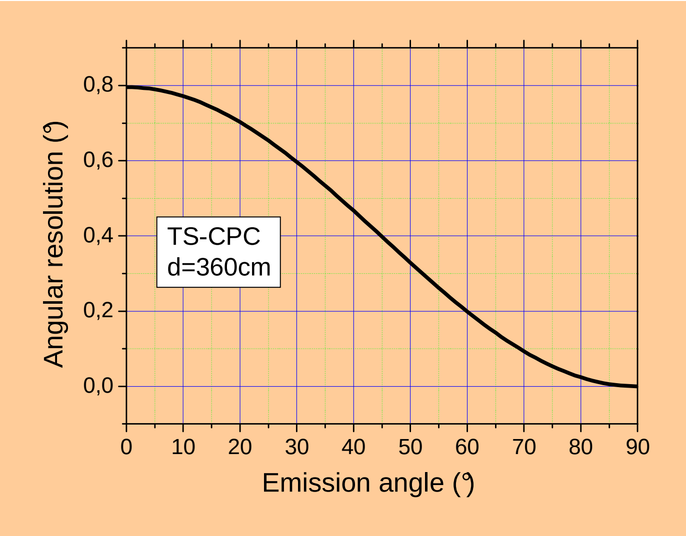
$$L_{rel}^{inv}(\delta,\varphi) = \frac{L^{inv}(\delta,\varphi)}{L^{inv}(0)} = \frac{\eta(\delta,\varphi)}{\eta(0)} = \eta_{rel}(\delta,\varphi)$$

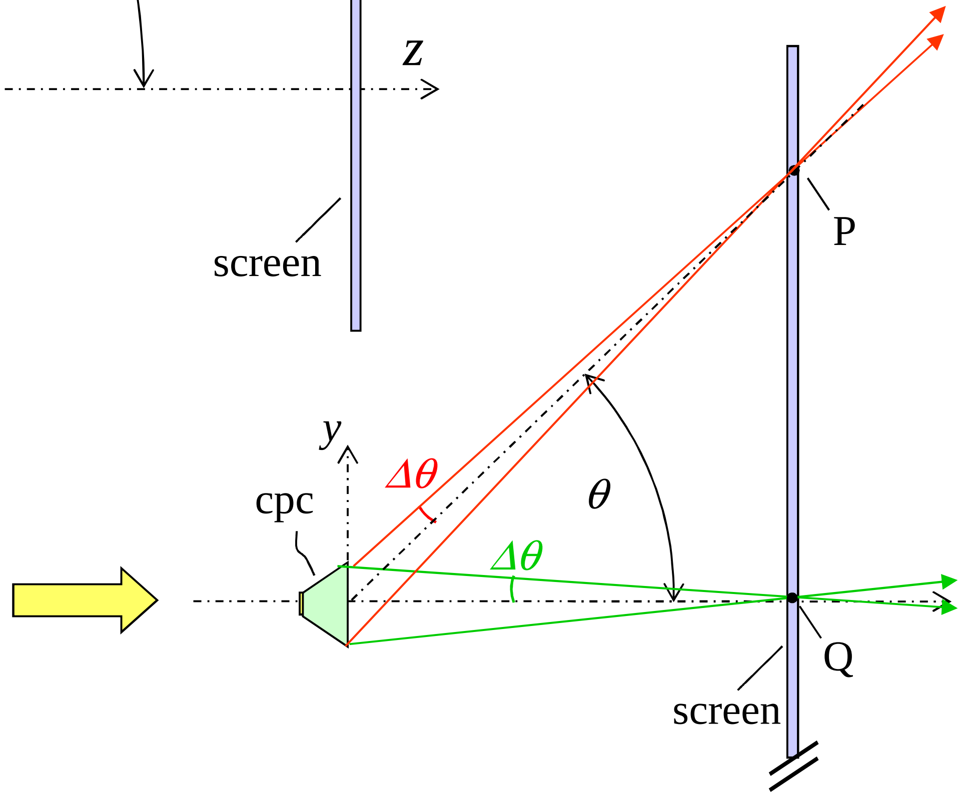
A detailed discussion about the theory of ILLUME is presented in the paper STuE2 of this Congress

Simplified theory of ILLUME (Angular resolution)

The screen must be far from the concentrator to increase resolution







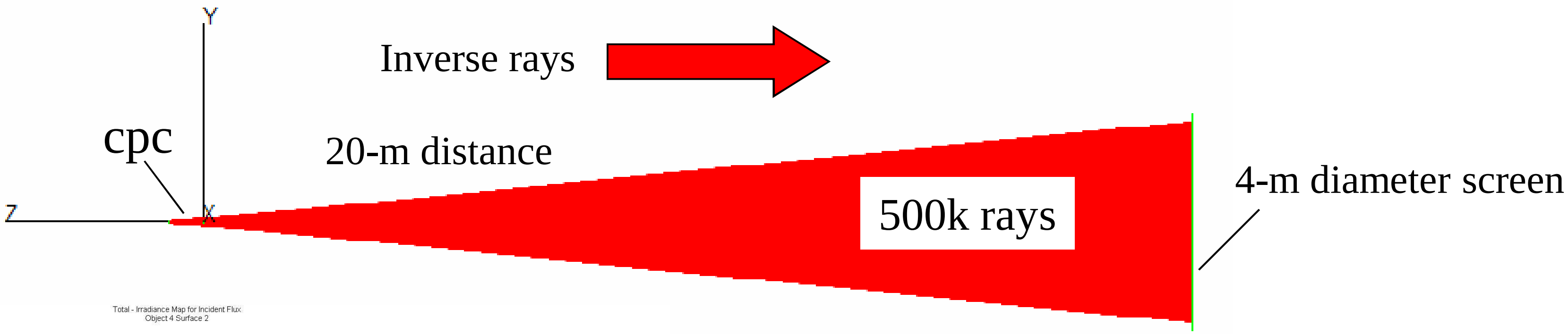
The angular resolution improves for points on the screen with high θ values

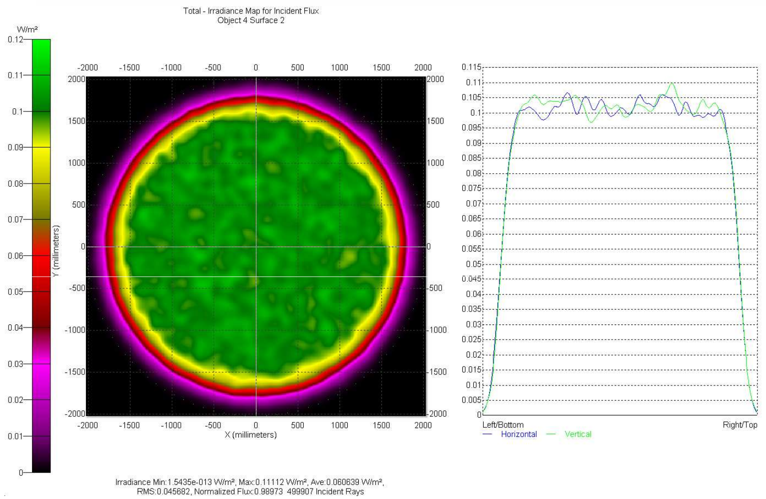
APPLICATIONS

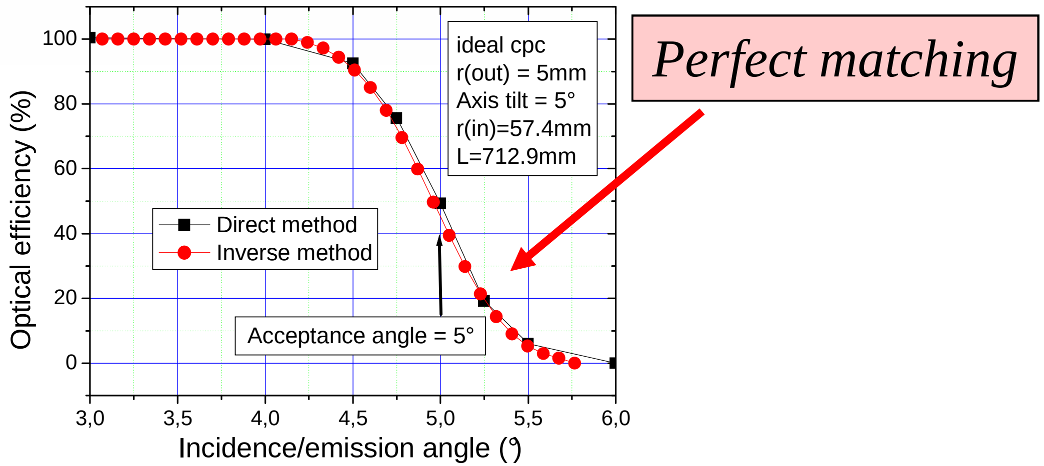
OF DIRECT AND INVERSE

METHODS

Ideal 3D-CPC – Optical Simulations







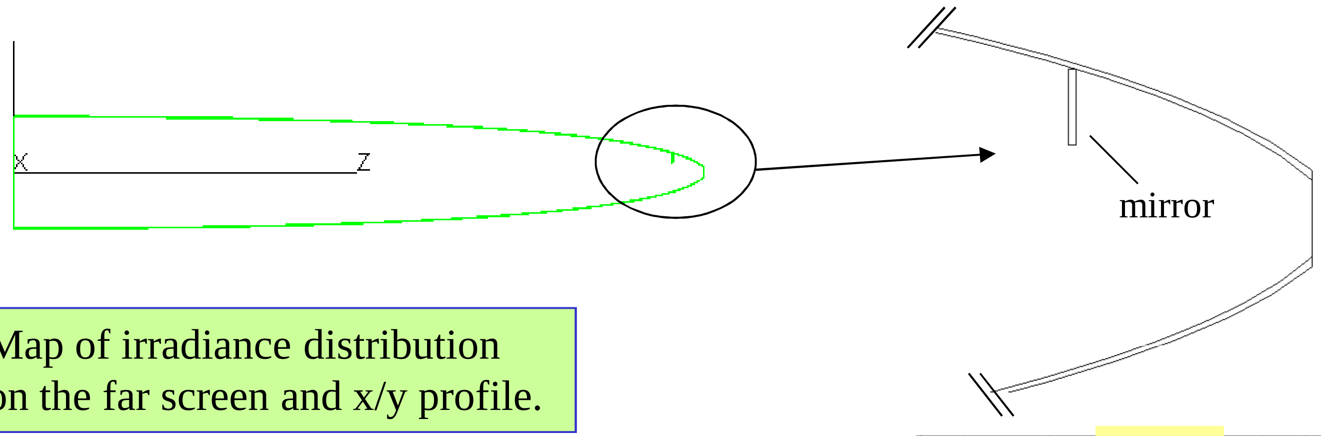
Map of irradiance distribution on the far screen and x/y profile.

Optical efficiency curves simulated for the direct and inverse method.

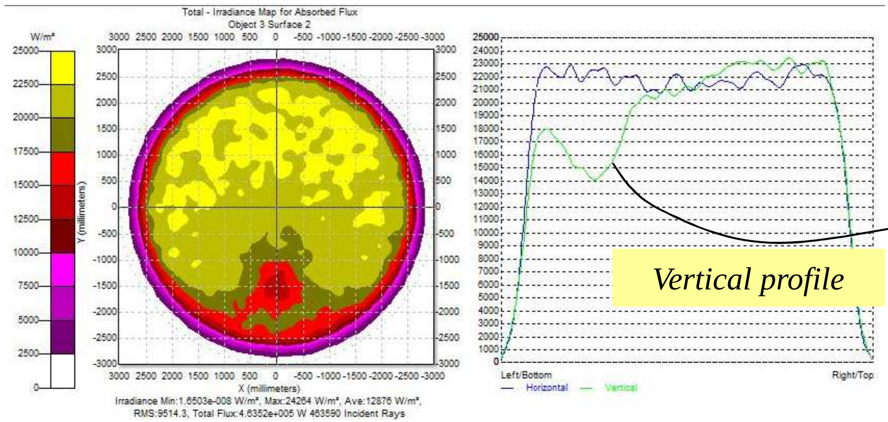
The inverse method requires one simulation!!
The direct method requires tens of simulations!!

Ideal 3D-CPC + mirror – Optical Simulations

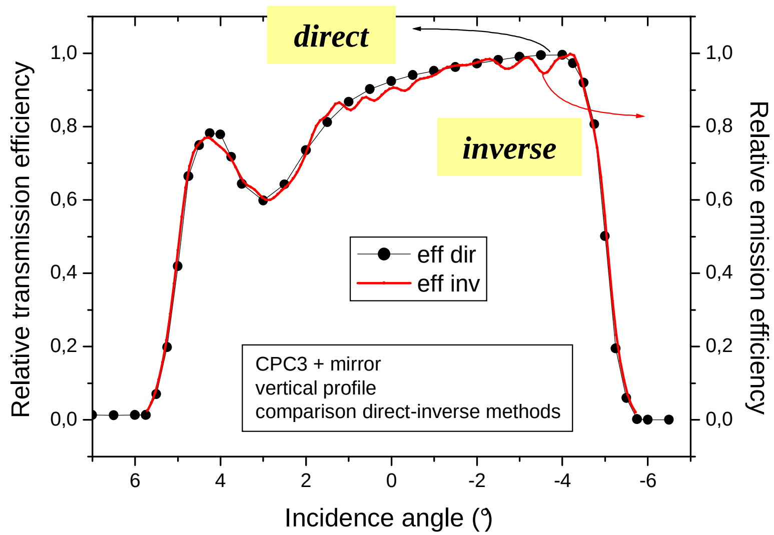
The inverse method works well at any condition!
To demonstrate it, we put an object (a mirror) inside the ideal concentrator and simulate again the direct and inverse methods



Map of irradiance distribution on the far screen and x/y profile.

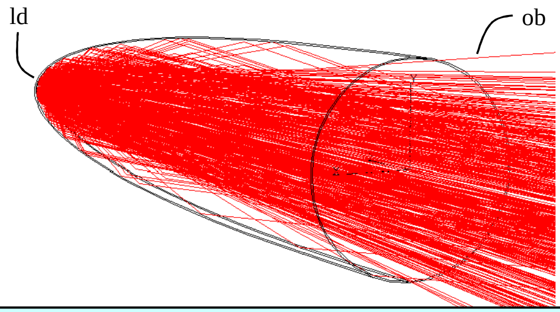


Map of inverse method



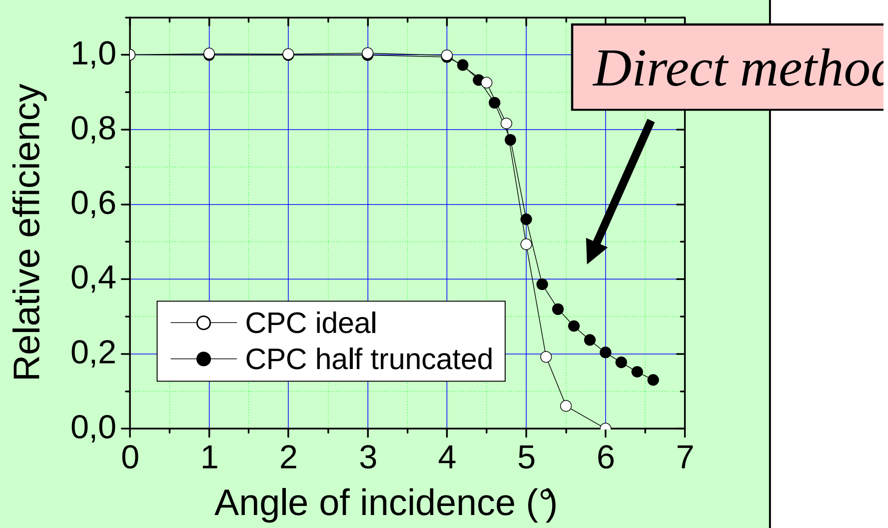
The vertical profiles are equal !!!

Half-Truncated 3D-CPC (HT-CPC) – Optical Simulations

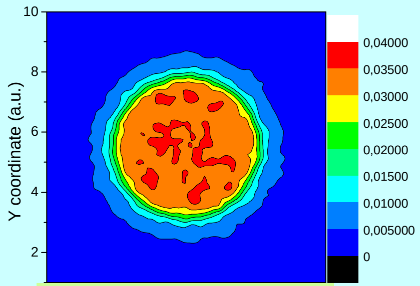


HT-CPC
r(in) = 52 mm
r(out) = 5 mm
L = 358 mm
Axis tilt = 5.1°

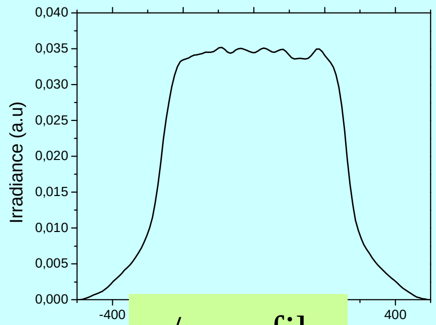
Direct analysis (TracePro®)



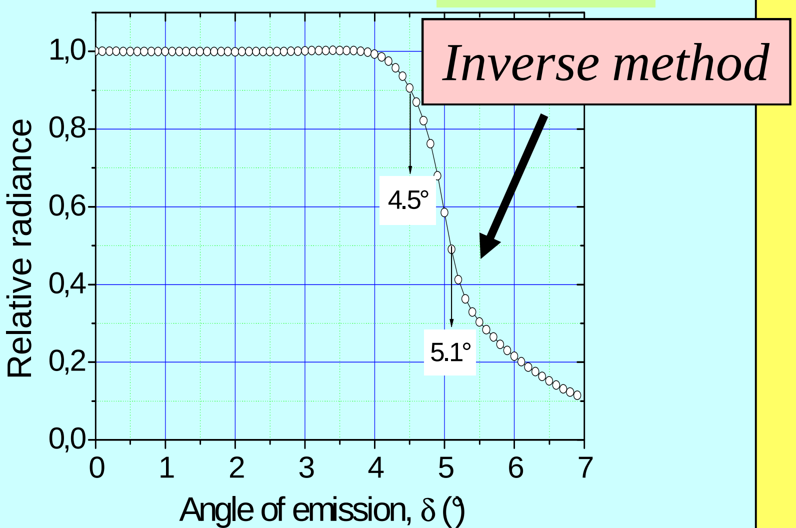
Inverse analysis (TracePro®)

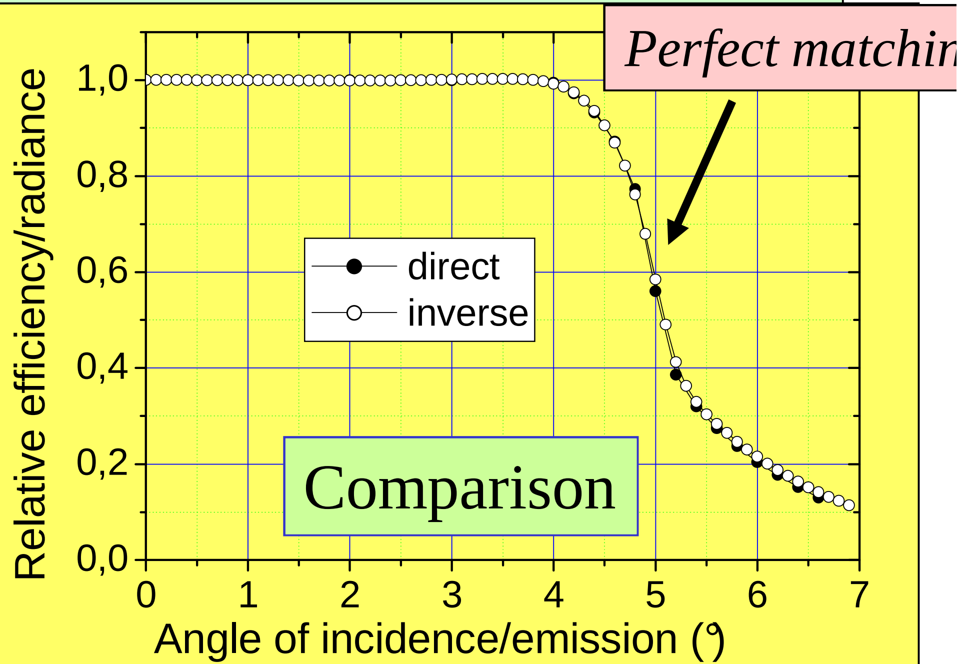


Irradiance map

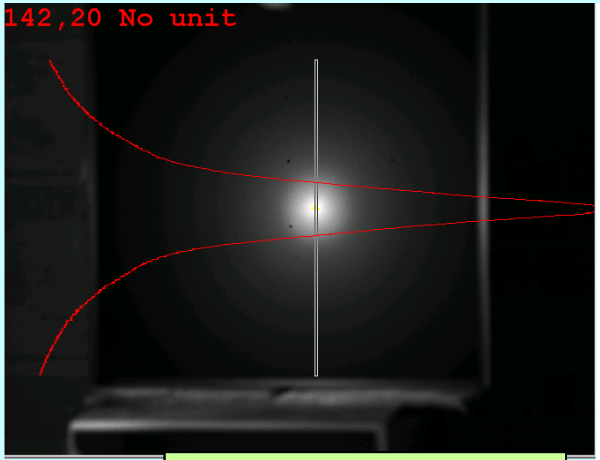


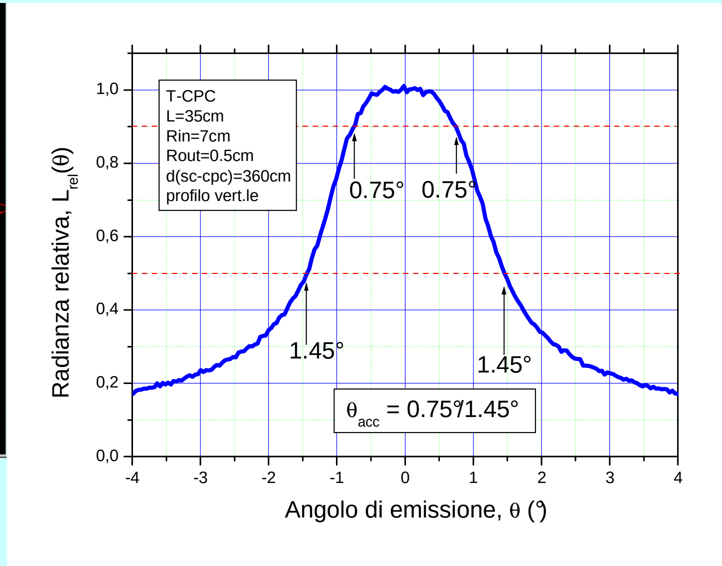
x/y profile





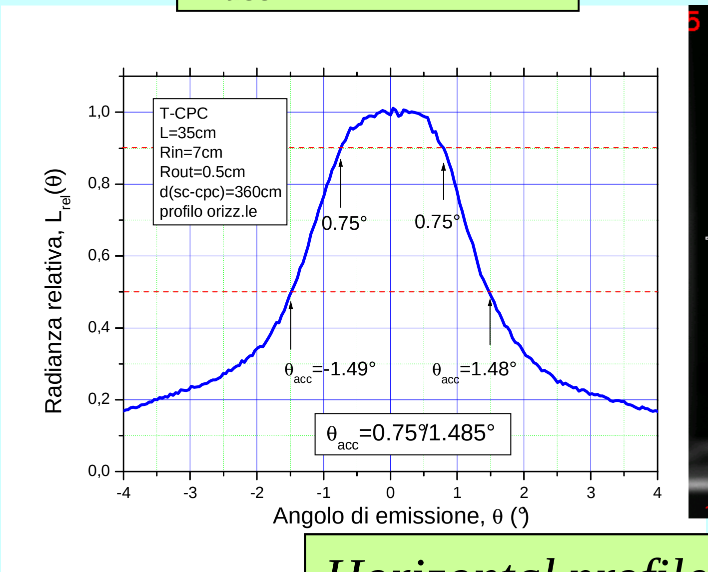
Truncated 3D-CPC (T-CPC) – Experimental results

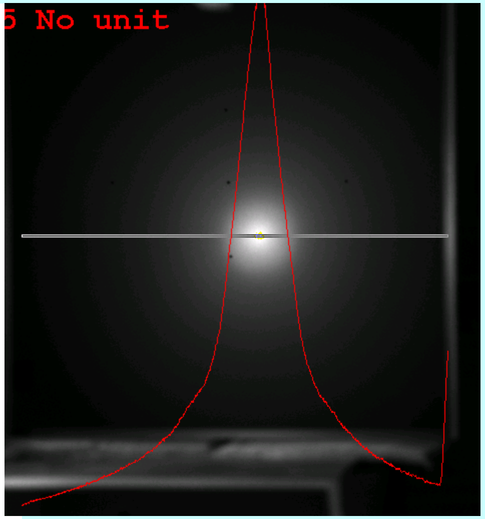




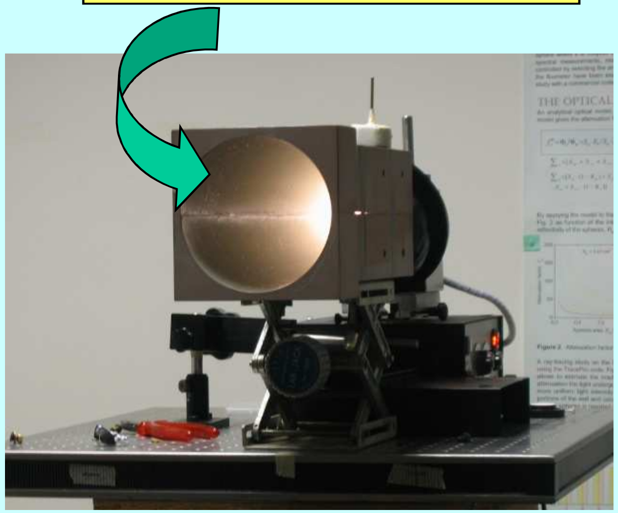
T-CPC
r(in) = 70 mm
r(out) = 5 mm
L = 358 mm

Vertical profile
θ_{acc} =0.75°/1.45°



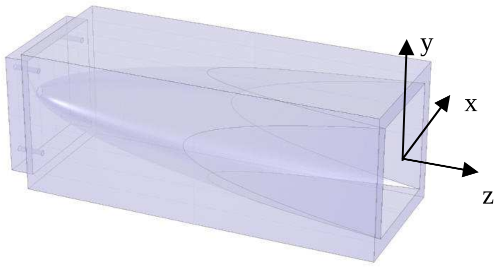


No mirror in the inner wall !!



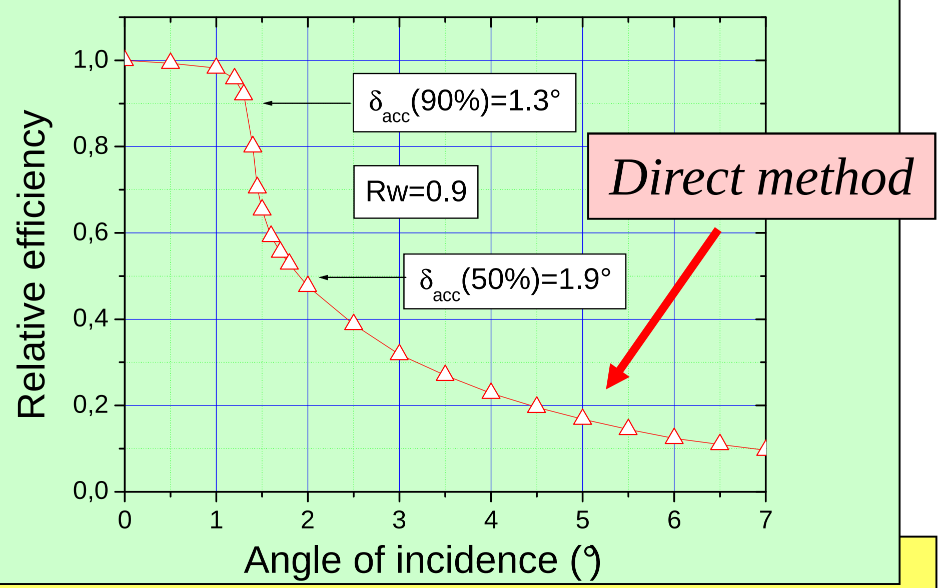
Horizontal profile
θ_{acc}=0.75°/1.48°

Truncated and Squared CPC (TS-CPC) – Optical Simulations

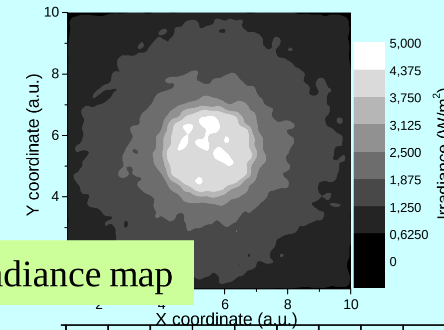


TS-CPC
l(in) = 100 mm
r(out) = 5 mm
L = 350 mm

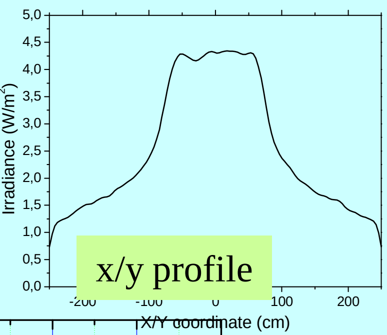
Direct analysis (TracePro®)



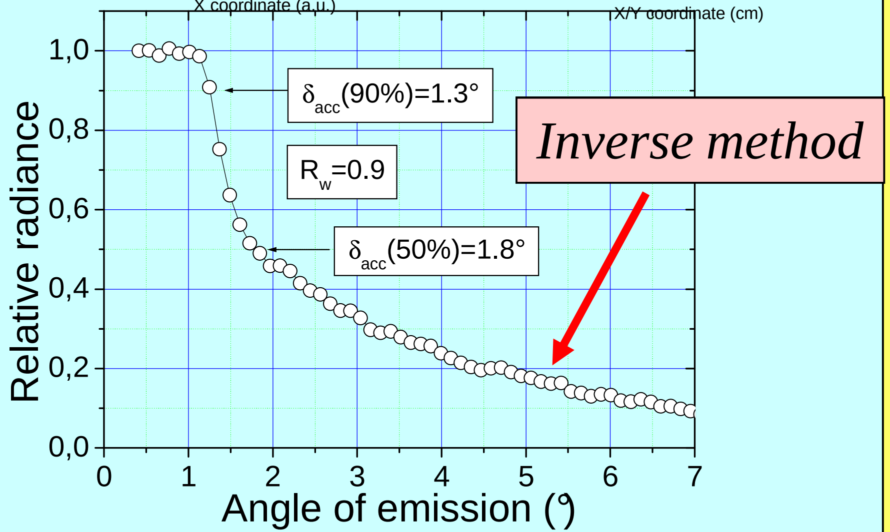
Inverse analysis (TracePro®)

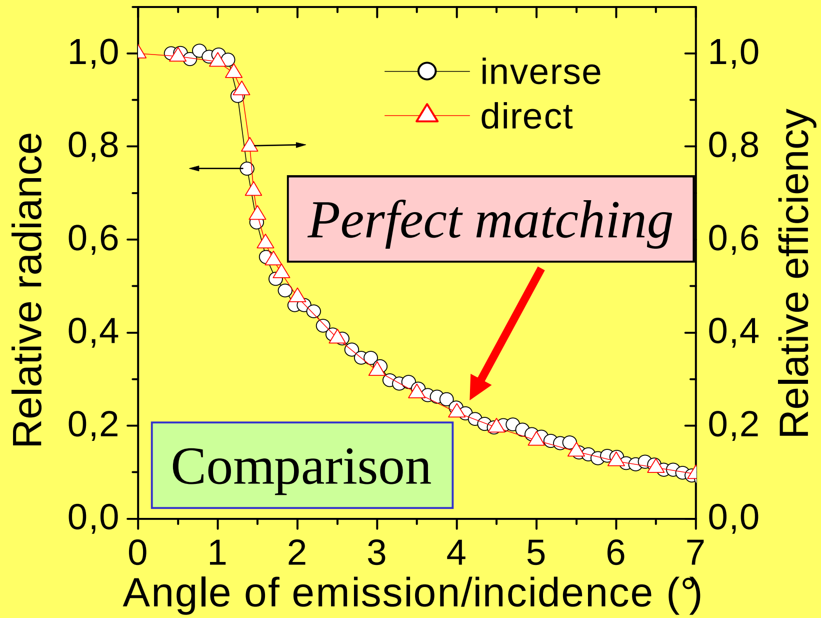


Irradiance map



x/y profile

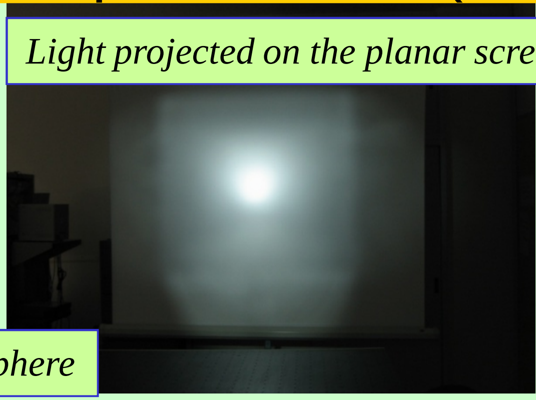


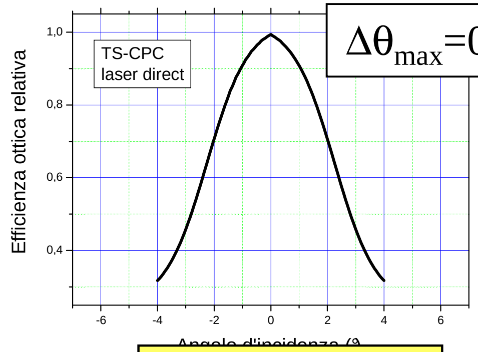


Truncated and Squared CPC (TS-CPC) – Experiments

Back illumination by an integrating sphere

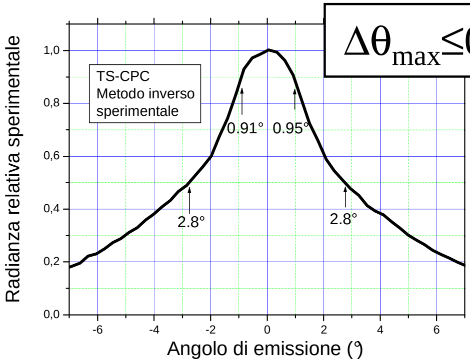
Light projected on the planar screen





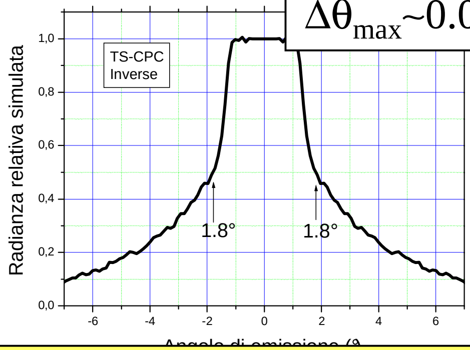
$\Delta\theta_{max}$=0.0°

Laser method



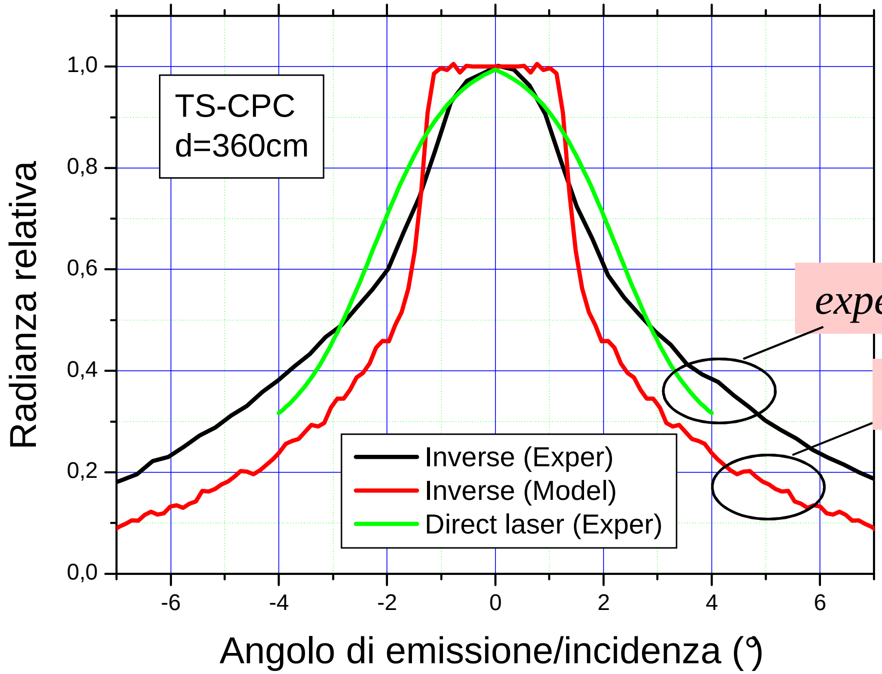
$\Delta\theta_{max}\leq$0.8°

Inverse experimental



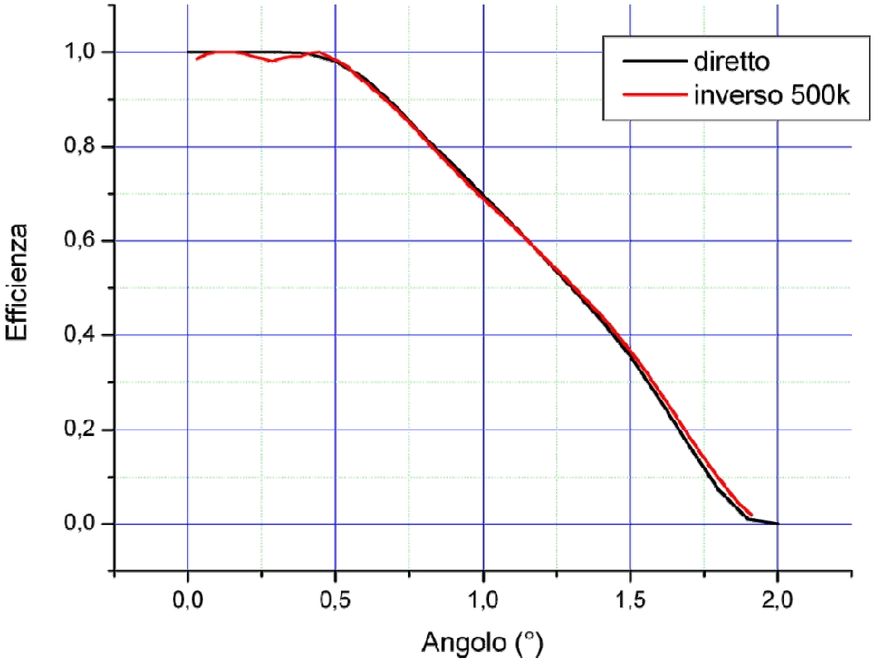
$\Delta\theta_{max}$~0.0°

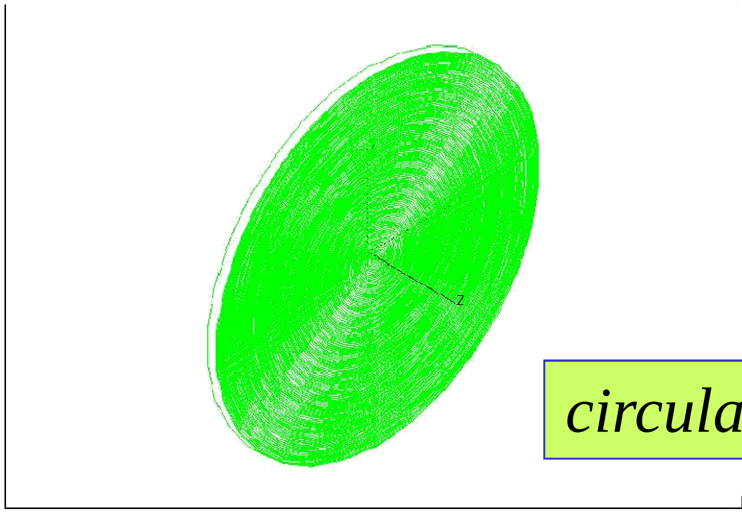
Direct and Inverse simulated



Comparison among the different methods

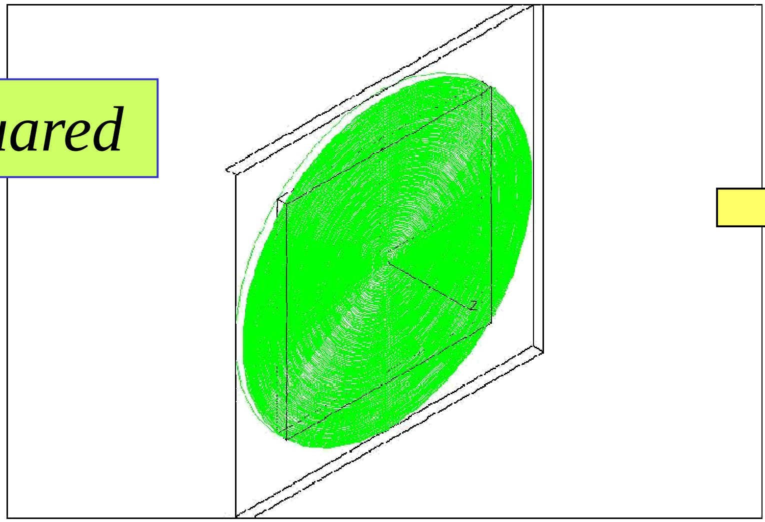
Fresnel lens

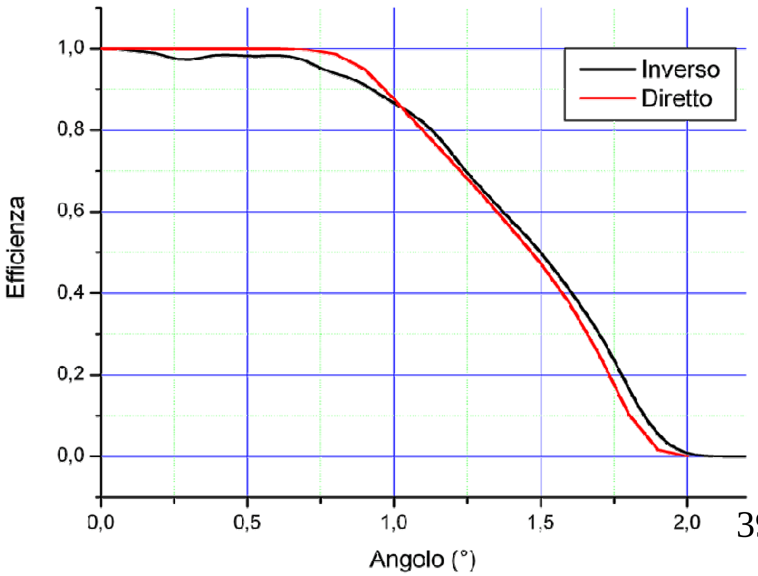




circular

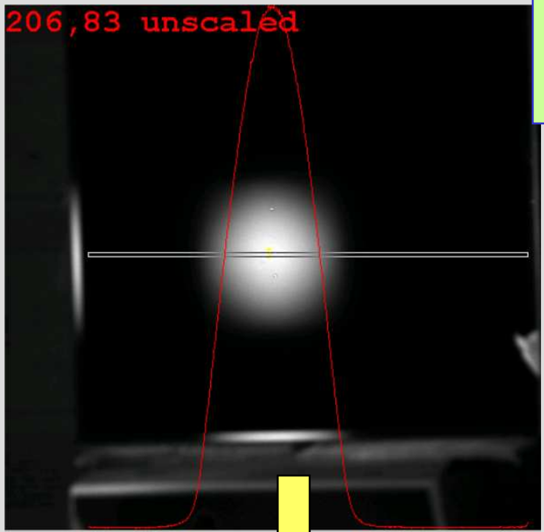
squared

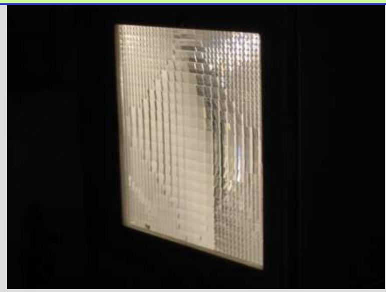


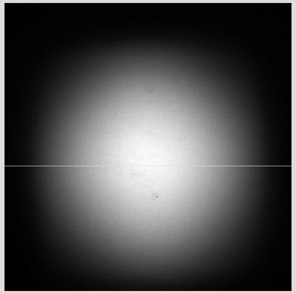


Refract"PhoCUS" Concentrator

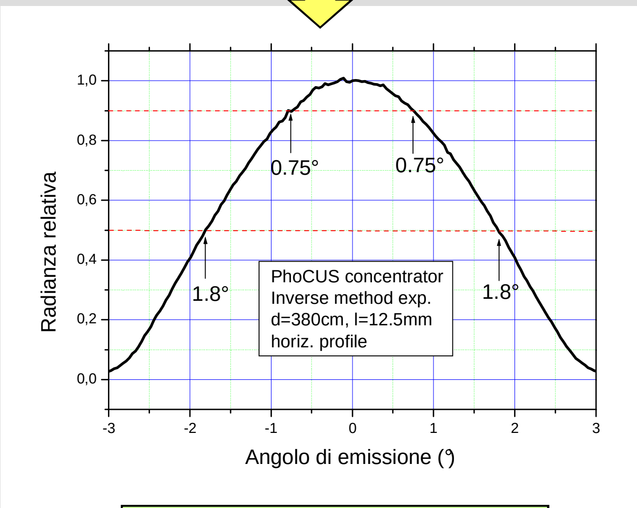
CPC-screen distance = 380 cm
Angular resolution: 1.0°



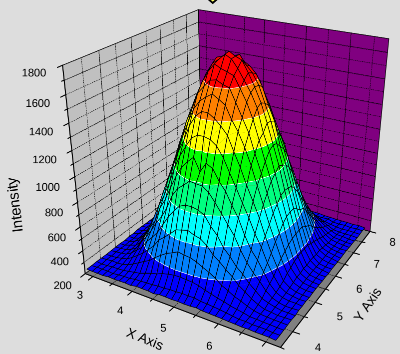




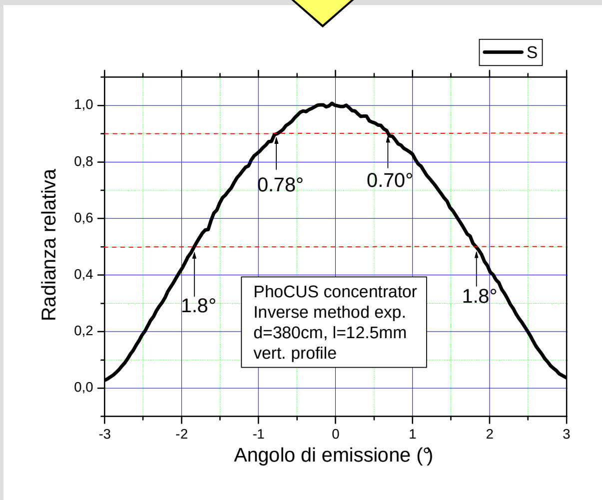
The image on the screen



Horizontal profile
θ_{acc}=0.75°/1.8°

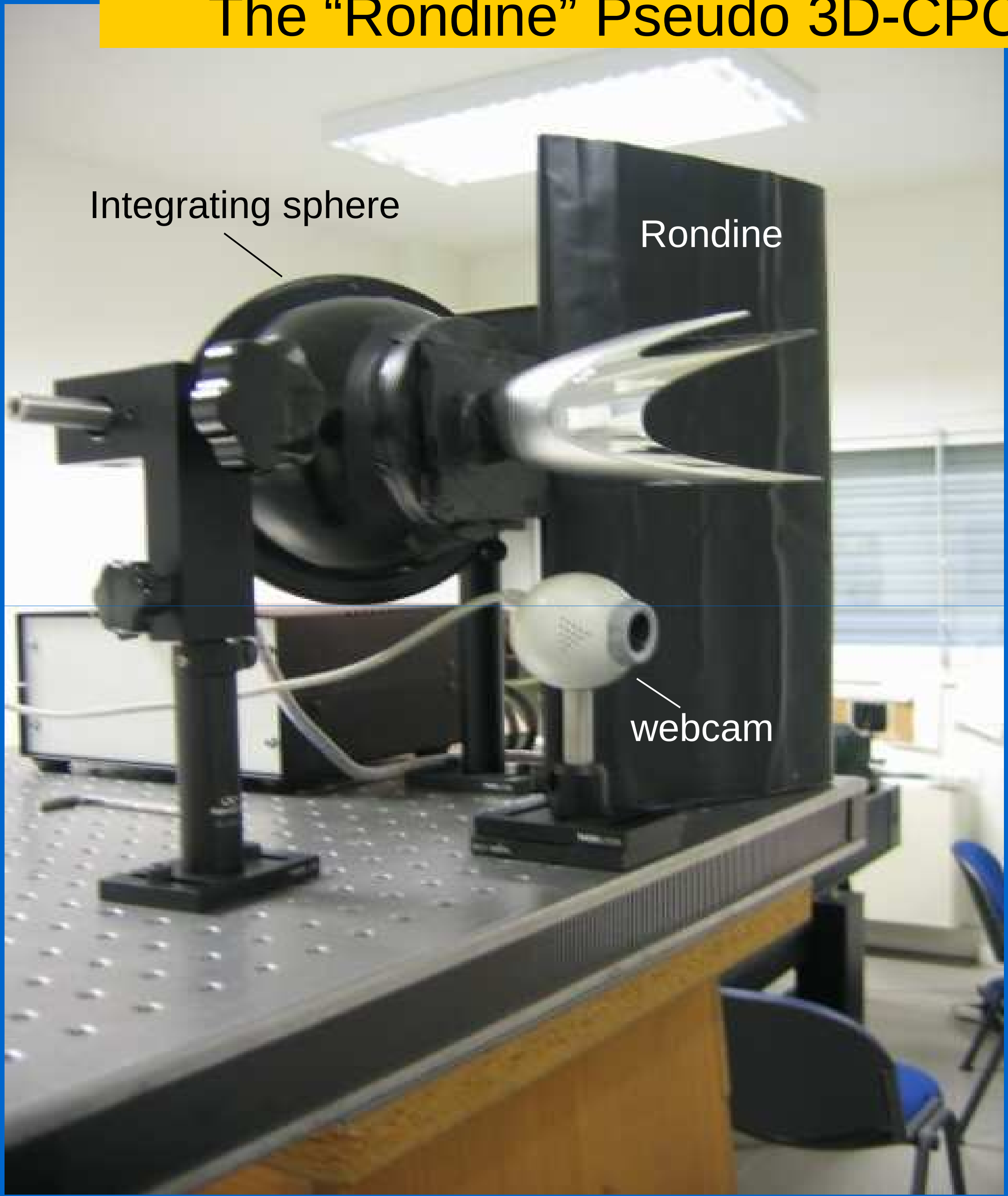


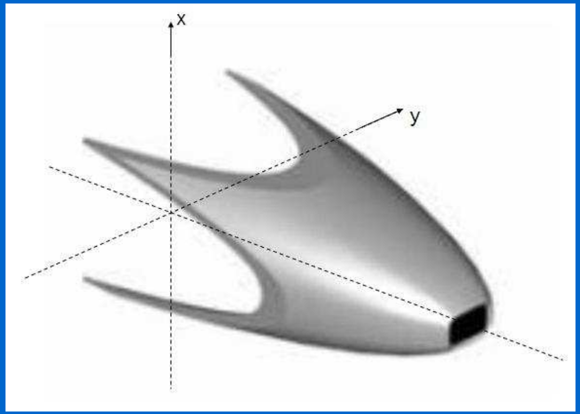
The irradiance distribution

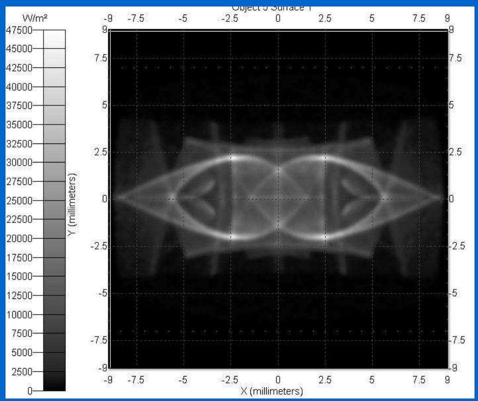


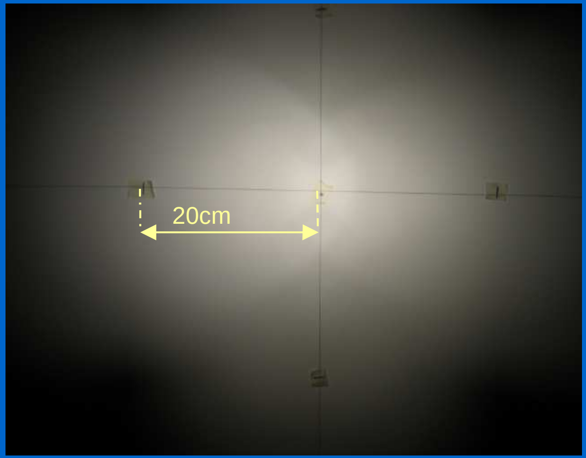
Vertical profile
θ_{acc}=0.75°/1.8°

The “Rondine” Pseudo 3D-CPC: The ILLUME set-up

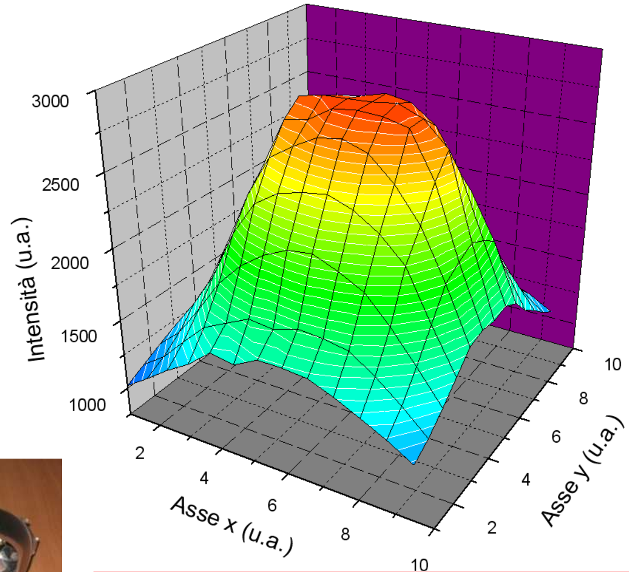




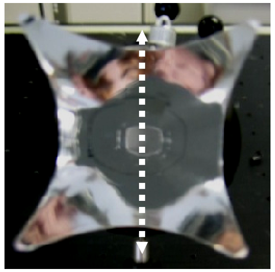


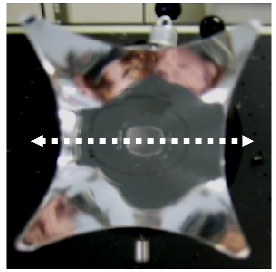


The “Rondine” Gen1 3D-CPC: Experimental results



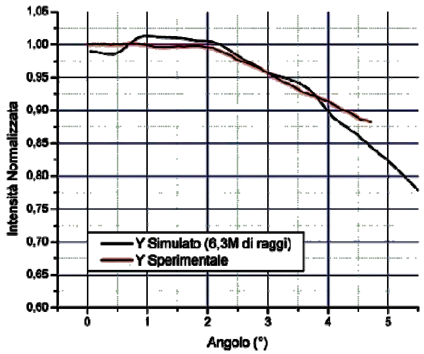
The irradiance map on the screen

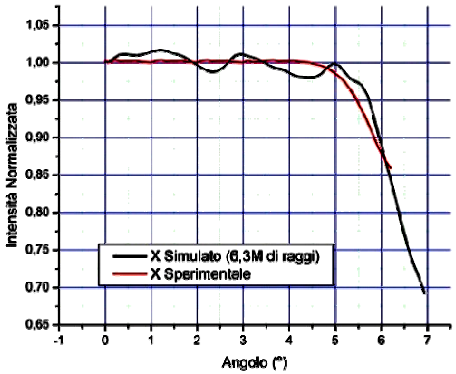




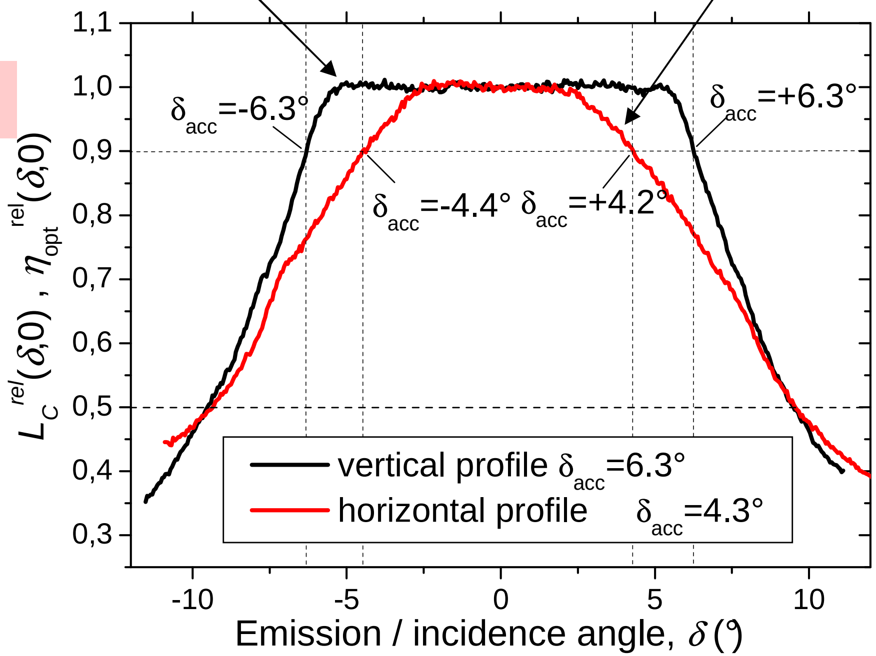
Vertical profile
θ_{acc} (90%) ≈ 6.3°

Horizontal profile
θ_{acc}(90%) ≈ 4.3°





Comparison between simulations and experiments



The “Rondine” Gen2 3D-CPC: Experimental results

CPC-screen distance = 229 cm
Angular resolution: 0.4°

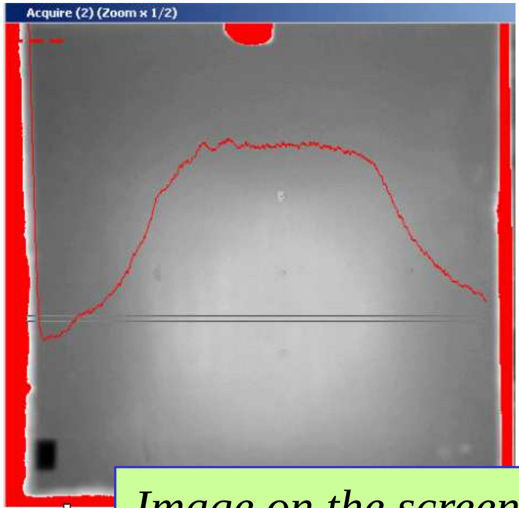
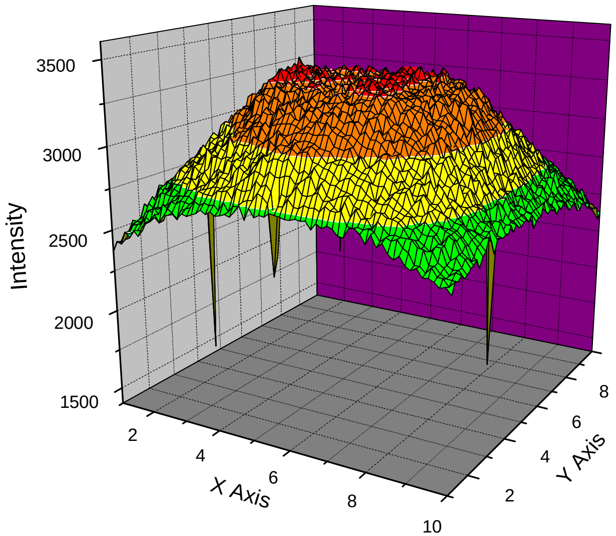
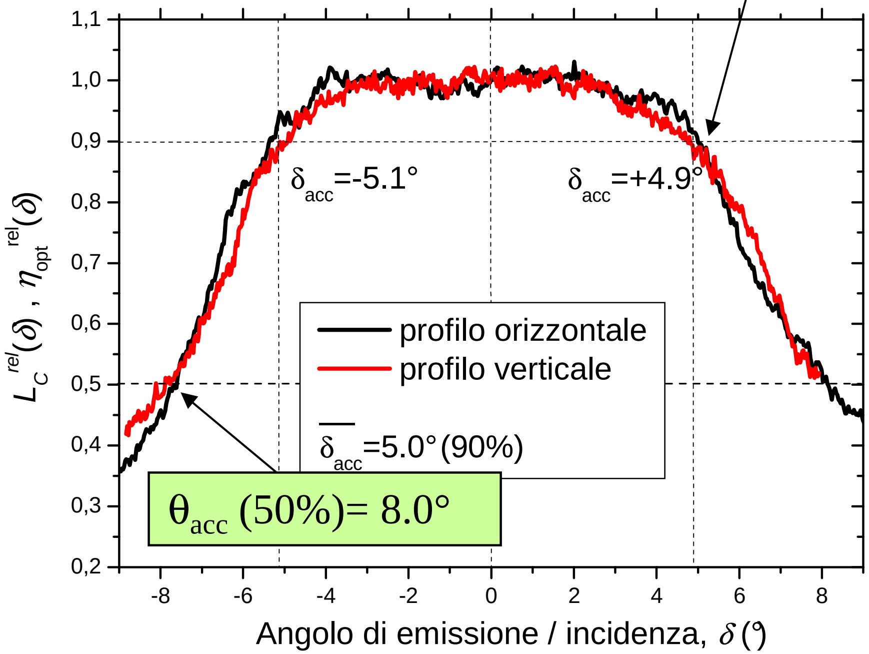


Image on the screen



Map of intensity

θ_{acc} (90%)= 5.0°



θ_{acc} (50%)= 8.0°

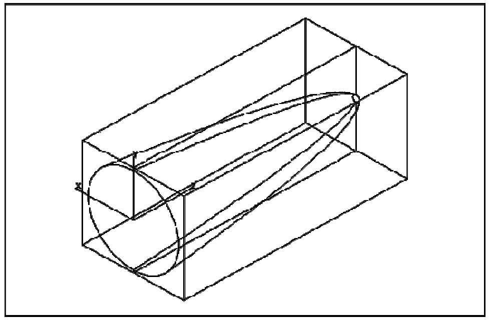
Summary of results of acceptance angles

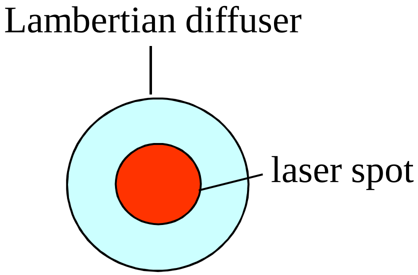
Method		Ideal 3D-CPC		TS-CPC		HT-CPC		RONDINE Gen1 Long side		RONDINE Gen1 Short side		RONDINE Gen2	
		90% Eff	50% Eff	90% Eff	50% Eff	90% Eff	50 % Eff	90% Eff	50% Eff	90% Eff	50% Eff	90% Eff	50% Eff
Dir.	Sim.	4.5°	5.0°	1.3°	1.9°	4.5°	5.1°	4.3°	7.5°	5.7-6.2°	8.5°		
	Exp.			1.1° (laser)	2.8° (laser)								
Inv.	Sim.	4.5°	5.0°	1.3°	1.8°	4.5°	5.1°	4.0-4.2°	8.1°	6.0-6.1°	8.6°		
	Exp.			0.9°	2.8°			4.2-4.3°	9.5°	5.8-6.3°	9.5°	5.0°	8.0°

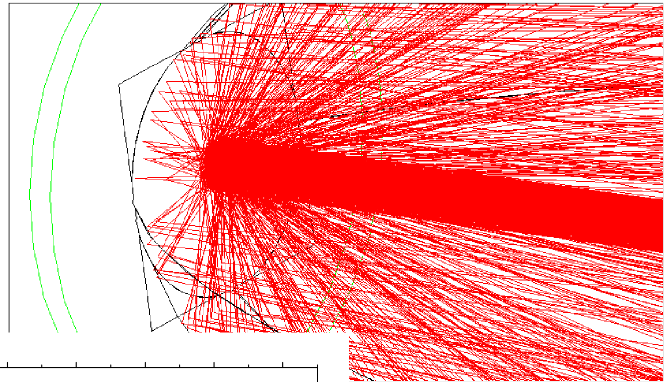
Table 1. Simulated and experimental acceptance angles for several 3D-CPCs analyzed with direct and inverse methods. Acceptance angles refer to 90% and 50% of maximum efficiency.

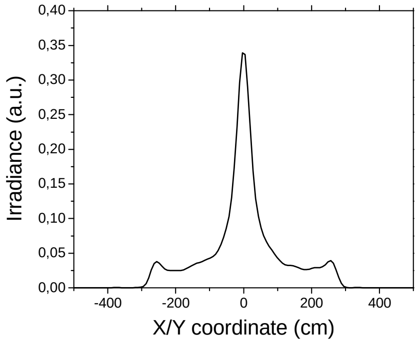
LOCAL ANALYSIS
OF
OPTICAL EFFICIENCY
(BY SIMULATIONS)

Laser beam at the center of receiver and variable cross-section

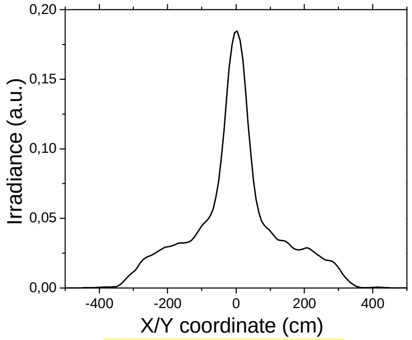




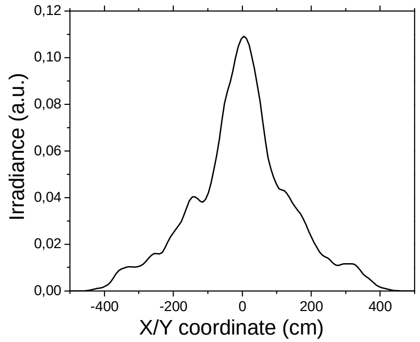




R= 0.05 mm

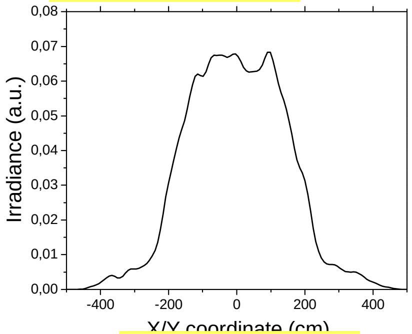


R= 0.5 mm

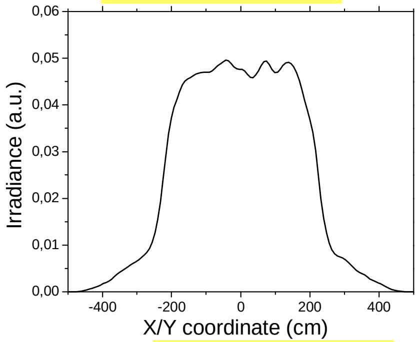


R= 1.0 mm

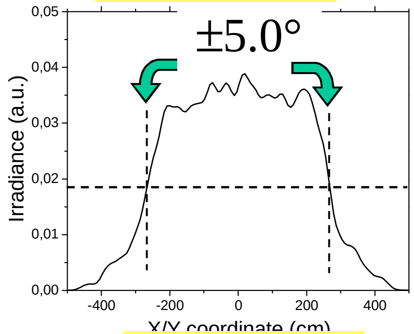
Angular interval: ± 9.5°



R= 2.5 mm

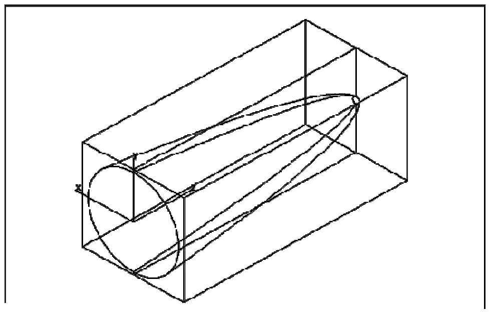


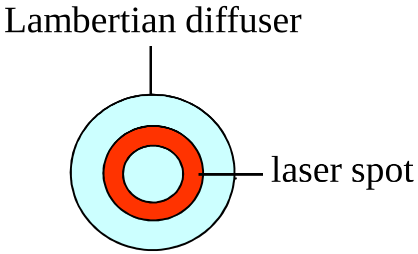
R= 3.5 mm

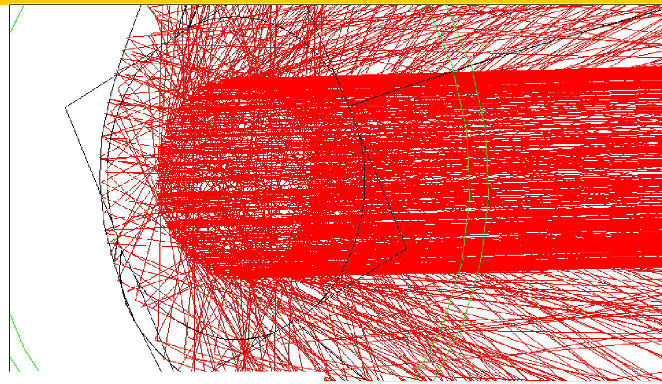


R= 5.0 mm

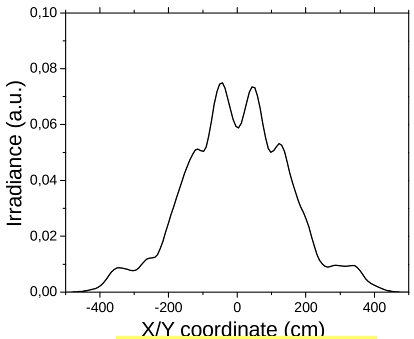
Ring-shaped Laser beam at the center of receiver and variable internal radius (constant area = π mm^2)



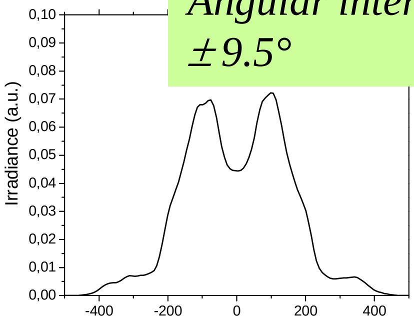




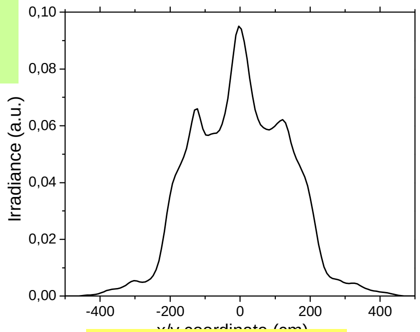
Angular interval: ±9.5°



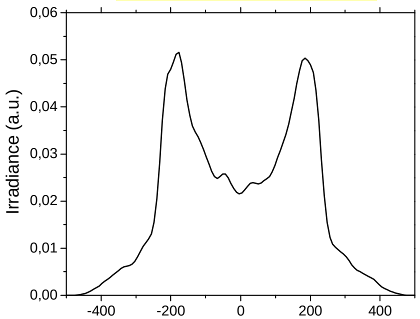
R_{int}= 0.5 mm



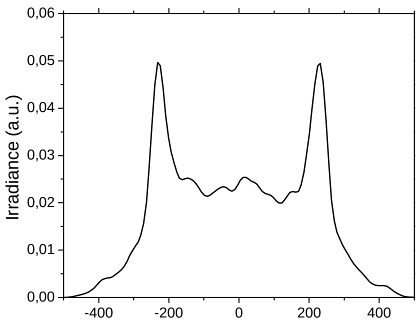
R_{int}= 1.0 mm



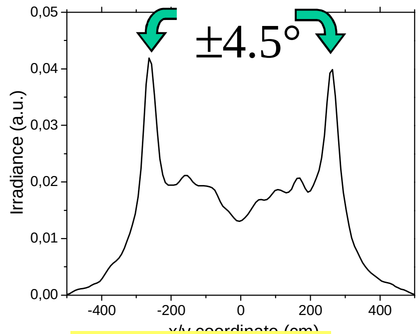
R_{int}= 2.0 mm



R_{int}= 3.0 mm

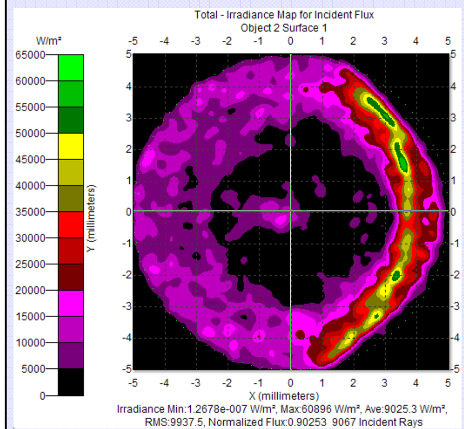


R_{int}= 4.0 mm



R_{int}= 4.9 mm

Direct analysis



Incident beam at 4.5°

RECENT DEVELOPMENTS

OF “ILLUME” THEORY

The absolute optical efficiency by ILLUME

Until now, the inverse method furnished the relative optical efficiency

$$\eta_{opt}(\delta,\phi) = \eta_{opt}(0) \cdot \eta_{opt}^{rel}(\delta,\phi)$$

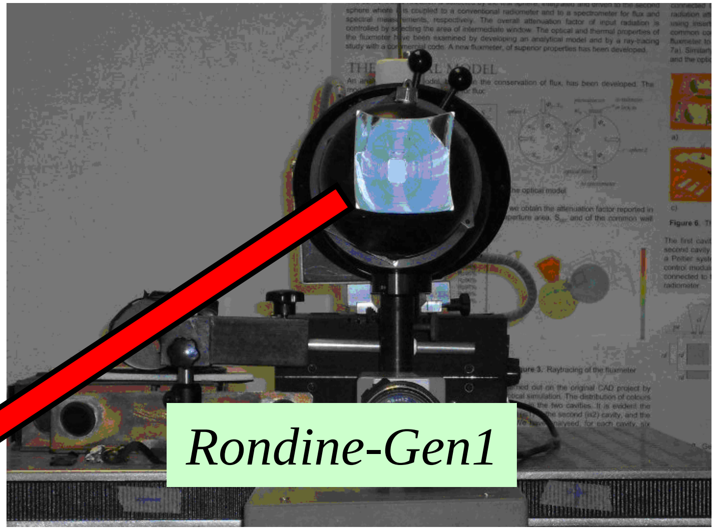
Now we show how to obtain also the absolute efficiency at 0° incidence

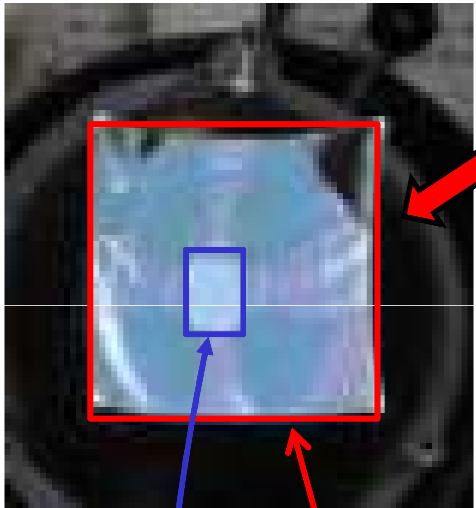
$$\eta_{opt}(0) = \frac{\overline{L}_C(0)}{L_{REC}}$$

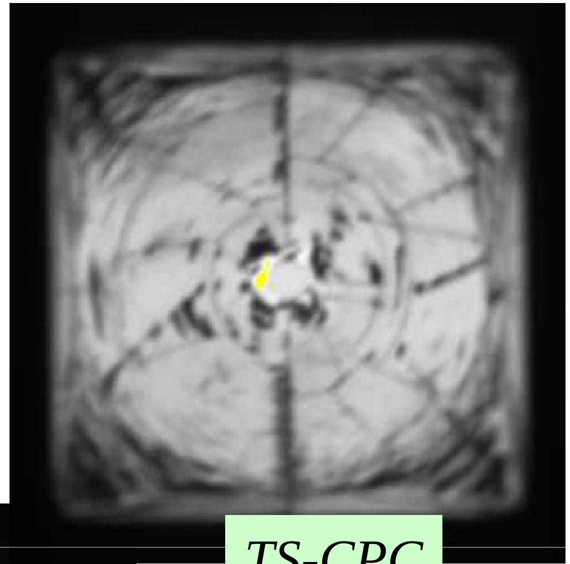
$\overline{L}_C(0)$ *is the average radiance of input aperture at 0° incidence*

L_{REC} *is the (average) radiance of the receiver (Lambertian source)*

The absolute optical efficiency by ILLUME

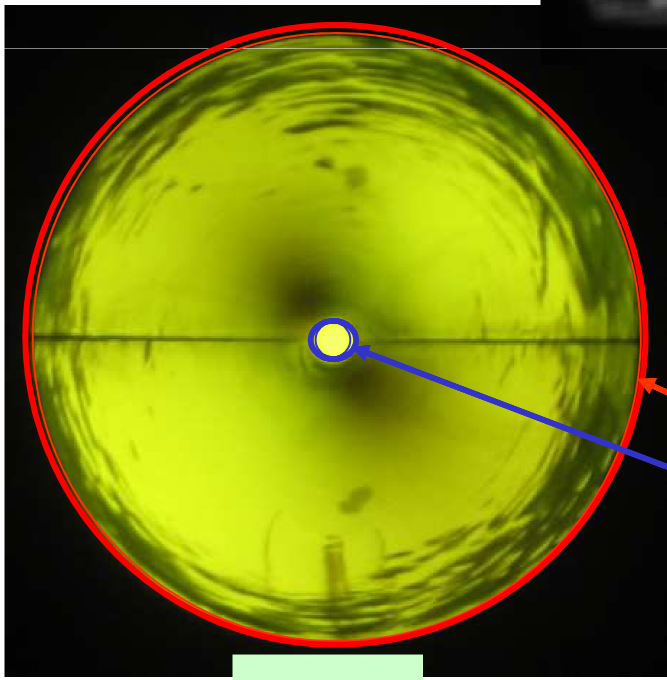






$$\frac{\overline{L}_C(0)}{L_{REC}} = \eta_{opt}(0)$$

Rondine-Gen1

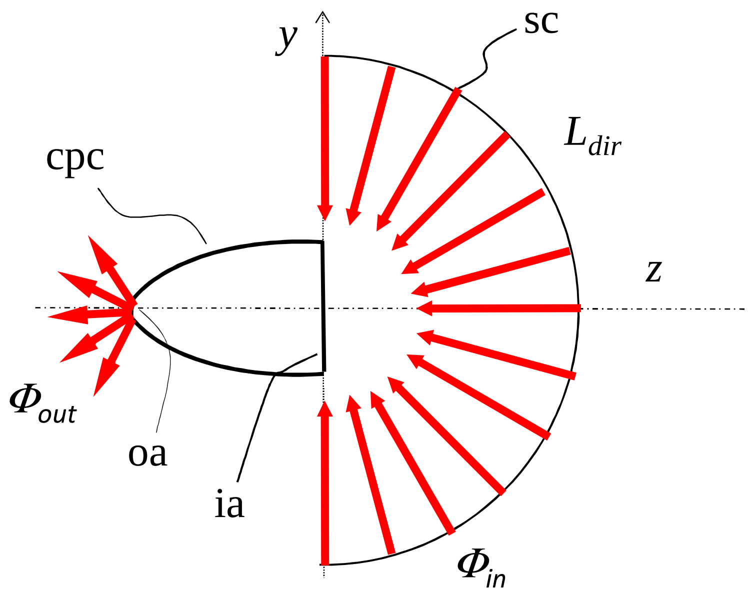


$$\frac{\overline{L}_C(0)}{L_{REC}} = \eta_{opt}(0)$$

TS-CPC

T-CPC

THE “DIRECT INTEGRAL METHOD” (DIM)



Overall (integral) transmission efficiency

DEFINITION OF NEW QUANTITIES
(Integral Direct Method)

We introduce also the following new optical quantities:

$$\eta_{dir}^{\text{int}} = \frac{\Phi_{dir}^{\tau}}{\Phi_{dir}^{in}} = 2 \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \eta_{dir}(\theta) = 2 \cdot \eta_{dir}(0) \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \eta_{dir}^{rel}(\theta)$$

direct integral optical transmittance

$$\alpha_{dir}^{\text{int}} = \frac{\Phi_{dir}^{\alpha}}{\Phi_{dir}^{in}} = 2 \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \alpha(\theta) = 2 \cdot \alpha(0) \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \alpha^{rel}(\theta)$$

direct integral optical absorbance

$$\rho_{dir}^{\text{int}} = \frac{\Phi_{dir}^{\rho}}{\Phi_{dir}^{in}} = 2 \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \rho(\theta) = 2 \cdot \rho(0) \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \rho^{rel}(\theta)$$

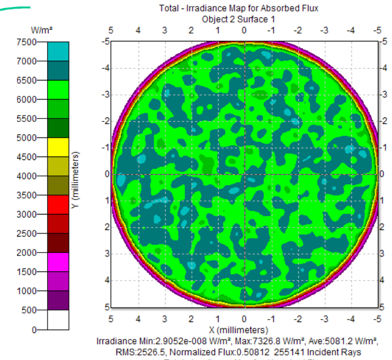
direct integral optical reflectance

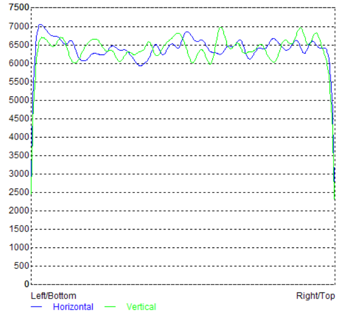
Where: $\eta_{dir}^{\text{int}} + \alpha_{dir}^{\text{int}} + \rho_{dir}^{\text{int}} = 1$

SPATIAL DISTRIBUTION OF FLUX AT THE OUTPUT OF SC
(Direct Integral Method)

Ideal concentrator (absence of absorption): $\alpha_{dir}(\theta_{in}, \varphi_{in}) = 0$

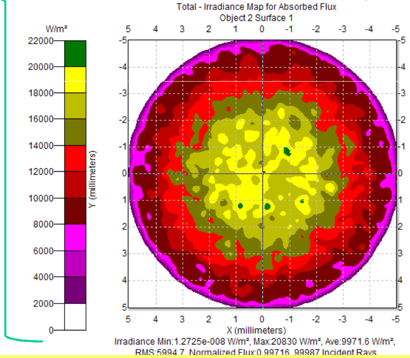
$R_w = 1.0$

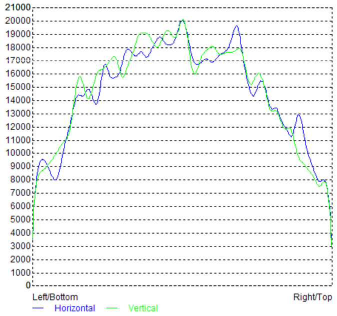




$\theta_{max} = 7° > \theta_{acc}$

Output flux spatially uniform !



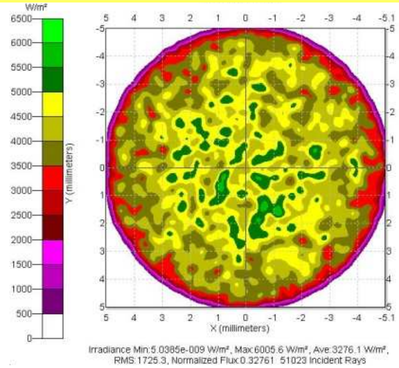


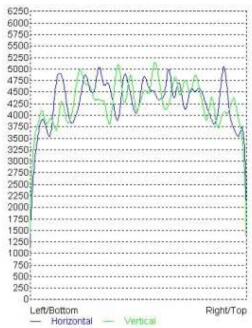
$\theta_{max} = 4° < \theta_{acc}$

Output flux spatially not uniform !

Non-ideal concentrator (absorption on the wall): $\alpha_{dir}(\theta_{in}, \varphi_{in}) \neq 0$

$R_w = 0.8$





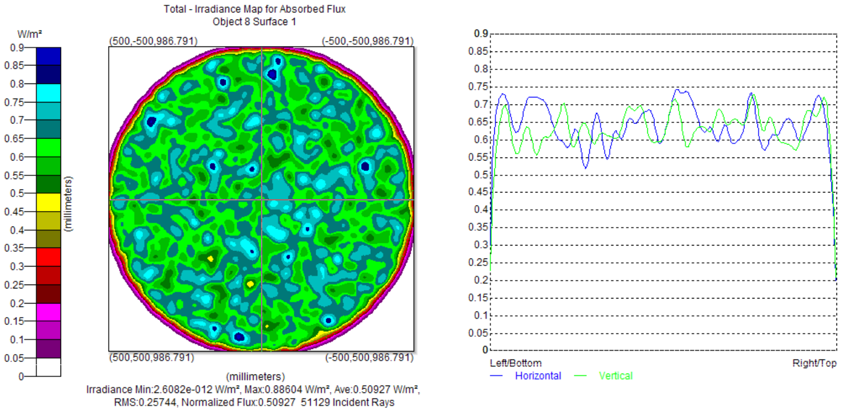
$\theta_{max} = 7° > \theta_{acc}$

Output flux spatially not uniform !

ANGULAR DISTRIBUTION OF FLUX AT THE OUTPUT OF SC
(Direct Integral Method)

Ideal concentrator (absence of absorption): $\alpha_{dir}(\theta_{in}, \varphi_{in}) = 0$

$R_w = 1.0$

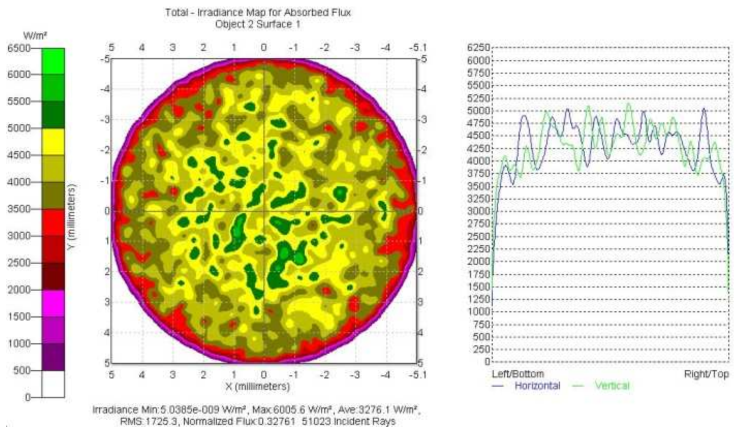


$\theta_{max} = 7° > \theta_{acc}$

Output flux Lambertian!

Non-ideal concentrator (absorption on the wall): $\alpha_{dir}(\theta_{in}, \varphi_{in}) \neq 0$

$R_w = 0.8$



$\theta_{max} = 7° > \theta_{acc}$

Output flux not Lambertian!

THE RADIANCE AT OUTPUT OF SC (Direct Integral Method)

Ideal concentrator (absence of absorption): $\alpha_{dir}(\theta_{in}, \varphi_{in}) = 0$

For an **ideal concentrator** the output flux is **uniform and Lambertian**.
The **output radiance** is:

$$L_{dir}^{out} = \frac{\Phi_{dir}^{\tau}}{\pi \cdot A_{out}} = \frac{2 \cdot L_{dir}^{in} \cdot A_{in}}{A_{out}} \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \eta(\theta) =$$

$$\ldots = 2 \cdot L_{dir}^{in} \cdot C_{geo} \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \eta(\theta)$$

C_{geo} = geometrical concentration ratio

Non-ideal concentrator (absorption on the wall): $\alpha_{dir}(\theta_{in}, \varphi_{in}) \neq 0$

For a **non ideal concentrator** the output flux is **non uniform and non Lambertian**.
The **average output radiance** is:

$$\overline{L}_{dir}^{out(\alpha)} = \frac{\Phi_{dir}^{\tau(\alpha)}}{\pi \cdot A_{out}} = 2 \cdot L_{dir}^{in} \cdot C_{geo} \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \eta_{\alpha}(\theta) =$$

$$\ldots = 2 \cdot L_{dir}^{in} \cdot C_{geo} \cdot \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot [1 - \alpha(\theta) - \rho(\theta)]$$

In general we have: $\overline{L}_{dir}^{out(\alpha)} \leq L_{dir}^{out}$

CONCLUSIONS

We have discussed two classes of methods of characterization of solar concentrators: “direct” and “inverse”, distinguishing the way the concentrator Is irradiated, if from the input or the output aperture.

The most important methods are the direct collimated method (DCM) and the inverse method (IM or ILLUME).

The DCM is largely used to obtain the transmission efficiency curve of the concentrator. It requires a lot of measurements at different angles of incidence of the collimated beam.

We have demonstrated here that also the IM method allows to obtain the same transmission efficiency curve of the concentrator.

However, we have also shown that the IM method is by far more convenient than DCM because it requires only one image to be recorded by a CCD in order to extract from it all the information about the angle-resolved optical efficiency of the concentrator.

THANKS FOR YOUR ATTENTION !