Simulation of Double-clad Scintillating Fibers
using the
GuideIt Ray-Tracing Package

Ioanna Chatziantonaki *

Dept. of Physics, University of Regina, Regina, SK Canada

Part of the work done while at the National and Kapodistrian University of Athens, Hellas

Abstract

We present an extensive study of the optical transmission of double-clad scintillating fibres through the ray-tracing package GuideIt, in order to investigate the properties of the fibres, to understand GuideIt analytically and to evaluate its suitability for future simulation needs.

*Corresponding author's e-mail address: chatziai@uregina.ca , YiannaCh@gmail.com

Contents

I. Sequences and Gates [1][2]

A standard double-clad optic fibre is depicted schematically below. The Regina group in GlueX has tested such fibres, having an outer diameter of 1 mm, from three manufacturers: Pol. Hi Tech, Kuraray and Bicron St. Gobain.

Fig. 1: Double-clad optic fiber (not to scale)

It is composed of three parts.

i. The core with a radius R_1=0.046cm, index of refraction (IOR) n_1=1.6 and attenuation length estimated around 350cm.

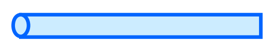


Fig.2: Construction of core

ii. The 1st cladding with a radius R_2=0.049cm, index of refraction (IOR) n_2=1.49 and attenuation length estimated around 1200cm.

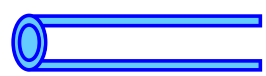


Fig.3: Construction of clad 1

iii. The 2nd cladding with a radius R_3=0.050cm, index of refraction (IOR) n_3=1.42 and attenuation length estimated around 1200cm.

Fig.4: Construction of clad 2

Each of these parts constitutes **"Sequence"** in the language of Guideit. A sequence is every virtual area in the simulation where a photon will change behaviour due to the different material that the area is made of. So the core is represented as the 1st sequence, the first clad as the 2nd sequence and the second clad as the 3rd sequence of our simulation.

Each sequence is a 3-D object (solid body) that is limited/created/surrounded by various surfaces. Let's describe the surfaces that consist the sequences of the above fibre.

Core: is represented by a cylinder and 2 disks.
Clad 1: is represented by 2 cylinders and 2 disks.
Clad 2: is represented by 2 cylinders and 2 disks.

Each surface is a **"Gate"** in the language of Guideit, because a photon can enter or exit a sequence through a surface and we can define the way each surface will function. Before doing that, it is convenient to show the categories of the gates (GATE TYPES) that Guideit provides and how each works.

- TOPGATE is a surface that books the photons falling on it and passes them to the next sequence. (We are going to use it for the photons which penetrate a surface).

- BOTGATE is a surface that books the photons falling on it and passes them back to the previous sequence. (We are going to use it for the photons which don't penetrate a surface and they are reflected by it).

- GATE is a surface that books the photons falling on it and then it terminates them. (We are going to use it for the photons, which impinge on a surface, penetrate it and then they continue to an area out of our interest of study).

Each surface in a sequence is characterised by one of the above GATETYPEs and should be given an individual gate-number different from the other surfaces of the sequence.
On the contrary if we define a surface as a NONE GATE, no gate –number will be given to it and the photons falling on it will not be booked and they will be terminated. (We characterise a surface as a NONEGATE when it is totally out of study).

Now we are ready to define each surface of each sequence of our optic fibre.

Let's begin with the core.
It consists of 3 surfaces so it has 3 gates. We give the following gate numbers to the surfaces:
Cylinder → gate # 1
Upstream disk → gate # 2
Downstream disk → gate # 3
Afterwards we will specify how each gate will function.
We define gate # 1, that is the cylinder, as a TOPGATE, because we want the photons that are going out of the cylinder to be booked and to pass to the next sequence that is the first clad. Then we define the gates 2 and 3 simply as GATEs because we just want to book the photons, which pass through them, and then to be terminated.

Clad 1 consists of 4 surfaces so it has 4 gates. We give the following gate numbers to the surfaces:
Inside cylinder → gate # 1
Outside cylinder → gate # 2
Upstream disk → gate # 3
Downstream disk → gate # 4
Then we define gate # 1, that is the inside cylinder, as a BOTGATE. We do this because we want the photons that pass that surface with direction from clad 1 to the core to enter the previous sequence, that is the core. Also the photons that fall on that

surface with direction from the core to the clad 1 without penetrating the surface should be reflected back to the core. Of course all these photons will be booked.
We define gate # 2 that is the outside cylinder as a TOPGATE, because we want the photons that are going out of the cylinder to be booked and to pass to the next sequence that is the second clad. Then we define the gates 3 and 4 simply as GATEs because we just want the photons, which pass through them, to be booked and then to be terminated.

Lastly the second cladding consists of 4 surfaces so it has 4 gates too. We give the following gate numbers to the surfaces:
Inside cylinder → gate # 1
Outside cylinder → gate # 2
Upstream disk → gate # 3
Downstream disk→ gate # 4
Then we define gate # 1 that is the inside cylinder as a BOTGATE. We do so because we want the photons that pass that surface with direction from the clad 1 to the core to enter the previous sequence that is the core. Also the photons that fall on that surface with direction from the clad 1 to the clad 2 without penetrating the surface to be reflected back to the core. Of course all these photons will be booked.
Then we define gates 2, 3 and 4 simply as GATEs because we just want to book the photons, which fall on them, and then to be terminated.
It should be noted that we give a gate number to the outside cylinder and we don't assign it as a NON GATE (as in previous works [3], [4]) because we wish to book the outgoing photons before terminating them.
Guideit gives us the chance to investigate in great detail the path of the photons through every sequence and to create various histograms of interest.

II. IOR and REALM [2]

At this point we are going to discuss about two settings of great importance for the correct configuration of running GuideIt.
For each surface one has to specify two Indices Of Refraction (IOR), the internal index and the external index. The REALM setting defines whether an incident photon is expected from inside or outside. Things are more complicated and the whole problem lies on the choice of definition of the "inside" and the "outside" area of a surface.
The first part of my study was made using the settings that are used by most persons studying optic fibres. The second part was made briefly using the settings that we consider as the correct ones. Here we are going to describe both sets of settings.

FIRST PART

		Inside IOR	Outside IOR	REALM
Core	***Cylinder***	1.6	1.49	Inside
	Upstream disk	1.6	1.6	Inside
	Downstream disk	1.6	1.6	Inside
Clad 1	***Inside Cylinder***	1.6	1.49	Outside
	Outside Cylinder	1.49	1.42	Inside
	Upstream disk	1.49	1.6	Inside
	Downstream disk	1.49	1.6	Inside
Clad 2	***Inside Cylinder***	1.49	1.42	Outside
	Outside Cylinder	1.42	1/1.6	Inside
	Upstream disk	1.42	1.6	Inside
	Downstream disk	1.42	1.6	Inside

Table 1

Lets focus on the two inside cylinders of claddings (in pink color on the table). REALM is set to "Outside" since incident photons are coming from core in the first occasion and from the 1st cladding in the second. So far so good, but what about IORs? It is easily observed that in both cases "inside" is considered not the IOR of the corresponding sequence but the IOR of the sequence before it. At the same time "outside" is considered the IOR of the sequence.

Since I disagree with that way of thinking I changed those settings and I created a

SECOND PART

		Inside IOR	Outside IOR	REALM
Core	***Cylinder***	1.6	1.49	Inside
	Upstream disk	1.6	1.6	Inside
	Downstream disk	1.6	1.6	Inside
Clad 1	***Inside Cylinder***	1.49	1.6	Outside
	Outside Cylinder	1.49	1.42	Inside
	Upstream disk	1.49	1.6	Inside
	Downstream disk	1.49	1.6	Inside
Clad 2	***Inside Cylinder***	1.42	1.49	Outside
	Outside Cylinder	1.42	1/1.6	Inside
	Upstream disk	1.42	1.6	Inside
	Downstream disk	1.42	1.6	Inside

Table 2

Our opinion is that for each sequence "inside" is whatever belongs to it and is contained in it. So although we agree with the REALM settings, we changed the IORs in both inside cylinders of both claddings (cyan color on the table).

III. Calculation of the mean speed of a photon traveling in core and clad 1

It is convenient to calculate the mean speed of a photon bouncing on the 3rd cylinder as to be able to calculate its path length later.
GuideIt calculates the mean time of flight of a photon exiting at the end of the fiber at each sequence. When a photon belongs to the second sequence (that is the clad 1) it definitely travels in both core and clad 1 bouncing on the surface of the 3rd cylinder that separates the two claddings as it is shown below for the blue ray:

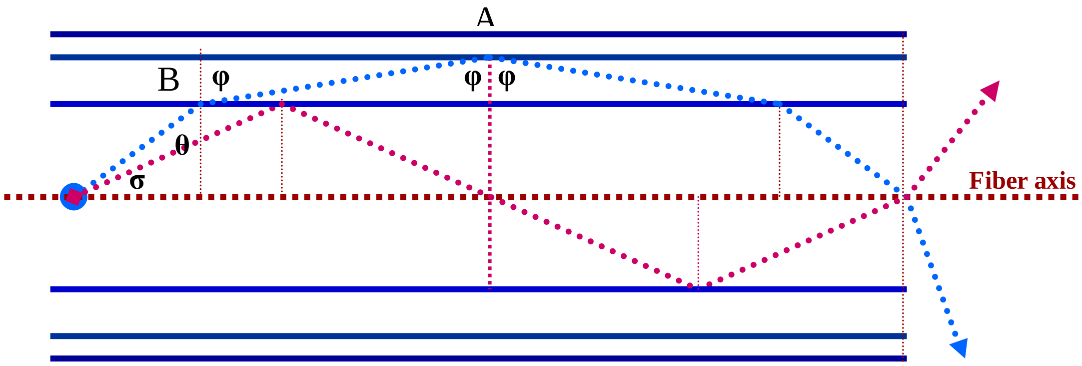


Fig.5: Trapped photons in core and in cladding 1 (not to scale).

Since the critical angle of refraction for the separating surface of the 2 claddings is:

Snell A: $$\sin\phi_c = \frac{n_3}{n_2} \Rightarrow \phi_c = 72.36^o$$

And using the Snell's law at B we find the emission angle for photons captured in the first cladding:

$$\sin\theta = \frac{n_2}{n_1}\sin\phi > \frac{n_2}{n_1}\sin\phi_c \Rightarrow \theta > 62.56^o \Rightarrow \sigma < 27.4^o$$

The mean speed of light can be calculated since the time of flight is known. In order to calculate the photon path approximately the refraction is neglected (because the thickness of the clad 1 is the 3% of the diameter of the core) so that the photon path is assumed as linear (since the angles are very small too) as it is shown at the figure below:

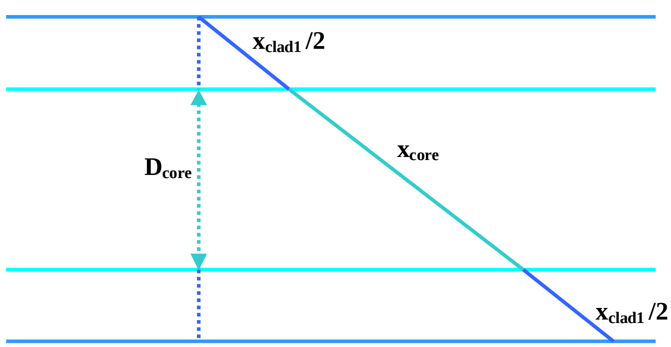


Fig.6: Double-clad optic fiber (not to scale) and geometric approximation to calculate the mean photon path.

The mean time of flight given from the histo_file (where the histograms are booked) for the 2nd sequence it is obviously the time of the photon traveling in the core plus the time traveling in the clad 1:

$$tof_1 = \frac{S_{core}}{c_{core}} + \frac{S_{clad1}}{c_{clad1}} \quad (1)$$

But this time should be equal to the total path divided by the mean speed of light traveling through core and clad 1:

$$tof_1 = \frac{S}{\bar{c}} \quad (2)$$

The total path is equal to the path in the core plus the path in the clad 1:

$$S = S_{core} + S_{clad1} \quad (3)$$

Knowing that the thickness of the first cladding is the 3% of the fiber diameter according to the figure it holds:

$$\frac{D_{core}}{3/100\, D_{fiber}} = \frac{x_{core}}{x_{clad1}/2} \Rightarrow \frac{0{,}92mm}{3/100\, 1mm} = \frac{2x_{core}}{x_{clad1}} \Rightarrow 92x_{clad1} = 6x_{core} \Rightarrow \boxed{x_{clad1} = \frac{3}{46}x_{core}} \quad (4)$$

This relation holds also for the total path in the core and the clad 1 that is:

$$S_{clad1} = \frac{6}{92}S_{core} \quad (5)$$

$$(1),(2) \Rightarrow \frac{S_{core}}{c_{core}} + \frac{S_{clad1}}{c_{clad1}} = \frac{S}{\bar{c}} \overset{(3)}{\Rightarrow}$$

$$\frac{S_{core}}{c_{core}} + \frac{S_{clad1}}{c_{clad1}} = \frac{S_{core} + S_{clad1}}{\bar{c}} \overset{(5)}{\Rightarrow}$$

$$\frac{S_{core}}{c_{core}} + \frac{6S_{core}}{92c_{clad1}} = \frac{1}{\bar{c}}\left(S_{core} + \frac{6}{92}S_{core}\right) \Rightarrow \qquad \frac{1}{c_{core}} + \frac{6}{92c_{clad1}} = \frac{98}{92\bar{c}} \Rightarrow$$

$$\frac{92c_{clad1} + 6c_{core}}{92c_{core}c_{clad1}} = \frac{98}{92\bar{c}} \Rightarrow \qquad \bar{c} = \frac{98c_{core}c_{clad1}}{92c_{clad1} + 6c_{core}} \Rightarrow$$

$$\boxed{\bar{c} = 18{,}8292558\, cm/ns \approx 18{,}83\, cm/ns}$$

Where $c_{core} = \frac{c_0}{n_{core}} = \frac{3 \cdot 10^{10}\, cm/s}{1{,}6} = 1{,}875 \cdot 10^{10}\, cm/s = 18{,}75\, cm/ns$ is the speed of light in the core and $c_{clad1} = \frac{c_0}{n_{clad1}} = \frac{3 \cdot 10^{10}\ {}^{cm}\!/\!_{s}}{1,49} = 2,01342282 \cdot 10^{10}\ {}^{cm}\!/\!_{s} \approx 20,13\ {}^{cm}\!/\!_{ns}$ is the speed of light in the 1st cladding.

By the way, we should take in to account that most of the photons, which are trapped in the 1st cladding, should exit from the core and are booked in the 1st sequence. For these photons we should use the mean speed of light we have just calculated above but we don't do it to simplify the whole procedure since the values do not differ greatly.
After this calculation of the mean speed of light when a photon travels through core and clad1 and exits at the end of the fiber in the clad 1 it is easy to calculate approximately the mean photon path S since the mean time of flight is booked by GuideIt.

$$Seq.1: S = c_{core} \times Tof \quad and \quad Seq.2: S = \bar{c} \times Tof$$

FIRST PART

1. Number of photons appearing at each sequence

The number of photons of each gate, as well as other statistical measurements, is booked in the out_file of each run of Guideit. It is a bit astonishing in the beginning to see that the total number of photons appearing at the first sequence exceed the number of propagated photons. Of course this is something that does not actually happen but it seems to happen at first glance. At this section we present the way of thinking in order to find the relation between the total number of photons appearing at a sequence and the number of photons booked from the various gates, as well as the percentages of lost photons to various reasons.

1.1 Ideal Simulations

It is convenient to start the study by using ideal surfaces and optical materials as to avoid the complexity of a full, realistic simulation. Therefore, at first attempt the BULK ATTENUATION option is set to NO and the option of the SURFACE ROUGHNESS is set to 1 for all surfaces. With those two settings we are assured that no photons will be absorbed due to the finite attenuation length of the optical materials and that no photons will be lost due to the fact that the surfaces are not perfectly smooth. The concept is to use the option that GuideIt gives to isolate sequences and study surfaces separately in a purely geometric fashion. 1000 photons were run in each of the simulations below.

1^{st} step:

GATE TYPE → GATE for all the surfaces.

That means that any photon having an interaction with a surface will be booked but then it will be terminated without continuing its path. The results are shown in the table below:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	936	0	0
Gate 2	29	0	0
Gate 3	35	0	0
Gate 4		0	0

Using the following symbols to represent the number of photons appearing at each gate and sequence.
N_p : propagated number of photons
$N_{S_i G_j}$: number of photons booked from the G_j Gate of the S_i Sequence
i=1,2,3 (since we have 3 sequences)
j=1,2,3 for the 1^{st} sequence (since it is consisted by 3 surfaces that is 3 gates)
j=1,2,3,4 for the 2^{nd} and the 3^{rd} sequence (since they are consisted by 4 surfaces that is 4 gates)
The former example of the table can take a more general expression:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1 G_1}$	0	0
Gate 2	$N_{S_1 G_2}$	0	0
Gate 3	$N_{S_1 G_3}$	0	0
Gate 4		0	0

Table 3

And it holds that $N_{S_1} = N_{S_1 G_1} + N_{S_1 G_2} + N_{S_1 G_3} = N_p$
It is expected not to have photons to the sequences 2 and 3 since the setting GATE to the first cylinder does not allow it.

2^{nd} step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1 (that is the cylinder of the first sequence) → TOPGATE

The objective here is to permit the photons to exit the first sequence through this cylinder and at the same time to book them. For the rest of the surfaces any photon having an interaction with them will be booked but then it will be terminated without continuing its path. The results are shown in the table below:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	940	2	0
Gate 2	34	890	0
Gate 3	26	20	0
Gate 4		28	0

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1 G_1}$	$N_{S_2 G_1}$	0
Gate 2	$N_{S_1 G_2}$	$N_{S_2 G_2}$	0
Gate 3	$N_{S_1 G_3}$	$N_{S_2 G_3}$	0
Gate 4		$N_{S_2 G_4}$	0

Table 4

And it holds that N_{S_2} $(=N_{S_2 G_1}+ N_{S_2 G_2}+ N_{S_2 G_3}+ N_{S_2 G_4})= N_{S_1 G_1}$

That means all photons that fall on the first cylinder and don't reach the end of the fibre because they are refracted, passed through to the second sequence.

3rd step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1 (that is the cylinder of the 1st sequence) → TOPGATE
Cylinder 2 (that is the inner cylinder of the 2nd sequence) → BOTGATE

Now the thought is to permit the photons to exit the first sequence through its cylinder and then the photons coming through the inner cylinder of the second sequence to enter the first sequence. At the same time, the ones that cannot be refracted can be reflected back to the 1st sequence. The results are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	952	3	0
Gate 2	23	903	0
Gate 3	28	25	0
Gate 4		21	0

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1 G_1}$	$N_{S_2 G_1}$	0
Gate 2	$N_{S_1 G_2}$	$N_{S_2 G_2}$	0
Gate 3	$N_{S_1 G_3}$	$N_{S_2 G_3}$	0
Gate 4		$N_{S_2 G_4}$	0

Table 5

And it holds that $N_{S_1}= N_p+N_{S_2 G_1}$
N_{S_2} $(=N_{S_2 G_1}+ N_{S_2 G_2}+ N_{S_2 G_3}+ N_{S_2 G_4})= N_{S_1 G_1}$

That means all photons that fall on the first cylinder are passed through to the second sequence and the sum of the photons appearing in the first sequence is equal to the number of propagated photons plus the photons entering again the first sequence after having travelled in the second sequence.

4th step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1(that is the cylinder of the 1st sequence) → TOPGATE
Cylinder 3(that is the outer cylinder of the 2nd sequence) → TOPGATE

Now the objective is to permit the photons to exit the first sequence through its cylinder and then the photons coming through the outer cylinder of the second sequence to enter the third sequence. The results are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	931	2	269
Gate 2	31	894	581
Gate 3	38	24	17
Gate 4		11	27

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1\,G_1}$	$N_{S_2\,G_1}$	$N_{S_3\,G_1}$
Gate 2	$N_{S_1\,G_2}$	$N_{S_2\,G_2}$	$N_{S_3\,G_2}$
Gate 3	$N_{S_1\,G_3}$	$N_{S_2\,G_3}$	$N_{S_3\,G_3}$
Gate 4		$N_{S_2\,G_4}$	$N_{S_3\,G_4}$

Table 6

And it holds that $N_{S_1}=N_p$

$N_{S_2}\,(=N_{S_2\,G_1}+N_{S_2\,G_2}+N_{S_2\,G_3}+N_{S_2\,G_4})=N_{S_1\,G_1}$

$N_{S_3}\,(=N_{S_3\,G_1}+N_{S_3\,G_2}+N_{S_3\,G_3}+N_{S_3\,G_4})=N_{S_2\,G_2}$

The sum of the photons appearing in the first sequence is equal to the propagated photons.
All photons that fall on the first cylinder (the cylinder of the first sequence) are passed through to the second sequence.
All photons that fall on the third cylinder (the outer cylinder of the second sequence) are provided to the third sequence.

5th step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1(that is the cylinder of the 1st sequence) → TOPGATE
Cylinder 3(that is the outer cylinder of the 2nd sequence) → TOPGATE
Cylinder 4(that is the inner cylinder of the 3rd sequence) → BOTGATE

Now the idea is to permit the photons to exit the first sequence through its cylinder and enter the second sequence then the photons coming through the outer cylinder of the second sequence to enter the third sequence. At the same time the photons coming through the inner cylinder of the third sequence will return to the second one, as well as the reflected ones. The results are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	935	196	262
Gate 2	33	914	590
Gate 3	32	48	31
Gate 4		39	31

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1\,G_1}$	$N_{S_2\,G_1}$	$N_{S_3\,G_1}$
Gate 2	$N_{S_1\,G_2}$	$N_{S_2\,G_2}$	$N_{S_3\,G_2}$
Gate 3	$N_{S_1\,G_3}$	$N_{S_2\,G_3}$	$N_{S_3\,G_3}$
Gate 4		$N_{S_2\,G_4}$	$N_{S_3\,G_4}$

Table 7

And it holds that $N_{S_1} = N_p$

$$N_{S_2} (= N_{S_2\,G_1} + N_{S_2\,G_2} + N_{S_2\,G_3} + N_{S_2\,G_4}) = N_{S_1\,G_1} + N_{S_3\,G_1}$$

$$N_{S_3} (= N_{S_3\,G_1} + N_{S_3\,G_2} + N_{S_3\,G_3} + N_{S_3\,G_4}) = N_{S_2\,G_2}$$

The sum of the photons appearing in the first sequence is equal to the propagated photons.
The photons appearing to the second sequence are the photons coming from the first sequence plus those coming from the third one.
All the photons falling on the outer cylinder of the second sequence are provided to the third sequence.

6th step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1(the cylinder of the 1st sequence)→ TOPGATE
Cylinder 2(the inner cylinder of the 2nd sequence)→ BOTGATE
Cylinder 3(the outer cylinder of the 2nd sequence)→ TOPGATE
Cylinder 4(the inner cylinder of the 3rd sequence)→ BOTGATE

Now the objective is to permit the photons to exit the first sequence through its cylinder and enter the second sequence, then, the photons coming through the outer cylinder of the second sequence will enter the third sequence. At the same time the photons coming backwards through the inner cylinder of the second sequence will return to the first sequence and the photons coming backwards through the inner cylinder of the third sequence will return to the second one. The photons that are not refracted by the separating surface of two optical mediums will be reflected and they will remain in the sequence they already are. Of course all the photons will be booked. For the rest of the surfaces any photon having an interaction with them will be booked but then it will be terminated without continuing it's path. The results are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	1072	207	319
Gate 2	72	1044	596
Gate 3	63	68	59
Gate 4		72	70

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1\,G_1}$	$N_{S_2\,G_1}$	$N_{S_3\,G_1}$
Gate 2	$N_{S_1\,G_2}$	$N_{S_2\,G_2}$	$N_{S_3\,G_2}$
Gate 3	$N_{S_1\,G_3}$	$N_{S_2\,G_3}$	$N_{S_3\,G_3}$
Gate 4		$N_{S_2\,G_4}$	$N_{S_3\,G_4}$

Table 8

And it holds that

$$N_{S_1}=N_p+N_{S_2\,G_1}$$

The number of photons appearing in the 1st sequence is the number of the propagated photons plus the ones coming from the 2nd sequence through its inner cylinder (G_1).

$$N_{S_2}=N_{S_1\,G_1}+N_{S_3\,G_1}$$

The number of photons appearing in the 2nd sequence is the number of the photons entering from the 1st sequence through its cylinder (G_1) plus the number of photons entering from the 3rd sequence through its inner cylinder (G_1).

$$N_{S_3}=N_{S_2\,G_2}$$

The number of photons appearing in the 3rd sequence is the number of photons entering from the 2nd sequence through its outer cylinder (G_2).

After all these steps one begins to understand the way the gates function and to realise that, in order to find out the behaviour of Guideit one has to isolate each surface first and then begin to combine them.

1.2 Realistic Simulations

After having that experience we are ready to consider optic fibres with 'real' parameters. That is the option of BULK ATTENUATION is set to YES and the attenuation lengths are set to 350cm for the core and 1200cm for the claddings **[1]**.
In addition the option of the SURFACE ROUGHNESS is set to 0.9999 for all the surfaces inside the fibre and 0.999 for the external surface, specifically the cylinder 5 or in other words the outer cylinder of the 3rd sequence, following the recommendation of the GuideIt manual.

We follow the same steps as in section 2.1. Lets introduce in advance the notation (as it concerns the percentages of photons lost due to various reasons), which is going to be used in the following steps.
a_i% is the percentage of photons that are attenuated in the i sequence
r_i% is the percentage of photons that are lost due to reflection on a rough surface in the i sequence and
$t_i\% = a_i\% + r_i\%$ is the total percentage of photons that is lost in the i sequence
i=1,2,3

1^{st} step:

GATE TYPE → GATE for all the surfaces.

That means that any photon having an interaction with a surface will be booked but then it will be terminated without continuing its path. The results we receive at the out_file are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	940	0	0
Gate 2	14	0	0
Gate 3	15	0	0
Gate 4		0	0
attenuated	2.9		
lost to reflection	0.2		

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1 G_1}$	0	0
Gate 2	$N_{S_1 G_2}$	0	0
Gate 3	$N_{S_1 G_3}$	0	0
Gate 4		0	0
attenuated	a_1		
lost to reflection	r_1		

Table 9

And it holds that $N_{S_1} = N_p\,(1-t_1)$

That means that the photons appearing in the first sequence are the propagated ones reduced by the total number lost.

It is expected not to have photons to the sequences 2 and 3 since the setting GATE to the first cylinder does not allow it.

2^{nd} step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1 (that is the cylinder of the first sequence) → TOPGATE

The idea is to permit the photons to exit the first sequence through this cylinder and at the same time to book them. For the rest of the surfaces any photon having an interaction with them will be booked but then it will be terminated without continuing its path. The results are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	933	1	0
Gate 2	19	885	0
Gate 3	15	4	0
Gate 4		5	0
attenuated	3.1	0.9	
lost to reflection	0.2	2.9	

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1 G_1}$	$N_{S_2 G_1}$	0
Gate 2	$N_{S_1 G_2}$	$N_{S_2 G_2}$	0
Gate 3	$N_{S_1 G_3}$	$N_{S_2 G_3}$	0
Gate 4		$N_{S_2 G_4}$	0
attenuated	a_1	a_2	
lost to reflection	r_1	r_2	

Table 10

And it holds that $N_{S_1}=N_p\,(1-t_1)$

$N_{S_2}= N_{S_1\,G_1}(1-t_2)$

This means that the photons appearing in the first sequence are the propagated ones, reduced by the total percentage of the lost ones. All the photons falling on the first cylinder are provided to the second sequence. Then they are reduced by the lost percentage and the remaining photons are detected (appear) at the 2nd sequence.

3rd step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1 (that is the cylinder of the 1st sequence) → TOPGATE
Cylinder 2 (that is the inner cylinder of the 2nd sequence) → BOTGATE
Now the objective is to permit the photons to exit the first sequence through its cylinder and then the photons coming through the inner cylinder of the second sequence to enter the first sequence. The results are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	934	1	0
Gate 2	19	886	0
Gate 3	15	4	0
Gate 4		5	0
attenuated	3.1	1	
lost to reflection	0.2	2.8	

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1\,G_1}$	$N_{S_2\,G_1}$	0
Gate 2	$N_{S_1\,G_2}$	$N_{S_2\,G_2}$	0
Gate 3	$N_{S_1\,G_3}$	$N_{S_2\,G_3}$	0
Gate 4		$N_{S_2\,G_4}$	0
attenuated	a_1	a_2	
lost to reflection	r_1	r_2	

Table 11

And it holds that $N_{S_1}=N_p\,(1-t_1)+N_{S_2\,G_1}$
$N_{S_2}=N_{S_1\,G_1}(1-t_2)$

The photons appearing in the first sequence are equal to the remaining of the propagated ones after being reduced by the percentage lost for various reasons plus the photons entering again the first sequence through the inner cylinder of the 2nd sequence.
The photons appearing in the 2nd sequence are equal to the remaining of the ones entering from the cylinder of the 1st sequence after being reduced by the percentage lost.

4th step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1 (that is the cylinder of the 1st sequence) → TOPGATE
Cylinder 3 (that is the outer cylinder of the 2nd sequence) → TOPGATE

This exercise is to permit the photons to exit the first sequence through its cylinder and then the photons coming through the outer cylinder of the second sequence to enter the third sequence. The results are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	933	4	256
Gate 2	20	890	585
Gate 3	18	4	0
Gate 4		0	0
attenuated	2.7	0.8	0
Lost to reflection	0.2	2.7	4.9

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1\,G_1}$	$N_{S_2\,G_1}$	$N_{S_3\,G_1}$
Gate 2	$N_{S_1\,G_2}$	$N_{S_2\,G_2}$	$N_{S_3\,G_2}$
Gate 3	$N_{S_1\,G_3}$	$N_{S_2\,G_3}$	$N_{S_3\,G_3}$
Gate 4		$N_{S_2\,G_4}$	$N_{S_3\,G_4}$
attenuated	a_1	a_2	a_3
lost to reflection	r_1	r_2	r_3

Table 12

And it holds that $N_{S_1} = N_p (1 - t_1)$

$N_{S_2} = N_{S_1 G_1} (1 - t_2)$

$N_{S_3} = N_{S_2 G_2} (1 - t_3)$

This means that the photons appearing in the first sequence are the propagated ones, reduced by the total percentage of the lost ones. All the photons falling on the first cylinder are provided to the second sequence. Then they are reduced by the lost percentage and the remaining photons are detected (appear) at the 2nd sequence. All the photons falling on the third cylinder are provided to the 3rd sequence. Then they are reduced by the lost percentage and the remaining photons are detected (appear) at the 3rd sequence.

5th step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1 (that is the cylinder of the 1st sequence)→ TOPGATE
Cylinder 3 (that is the outer cylinder of the 2nd sequence)→ TOPGATE
Cylinder 4 (that is the inner cylinder of the 3rd sequence)→ BOTGATE

Now the idea is to permit the photons to exit the first sequence through its cylinder and enter the second sequence then the photons coming through the outer cylinder of the second sequence allowed to enter the third sequence. At the same time the photons coming through the inner cylinder of the third sequence will return to the second one. The results are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	941	198	265
Gate 2	17	914	576
Gate 3	12	13	0
Gate 4		7	0
attenuated	2.7	1.2	0.1
Lost to reflection	0.3	6.2	7.2

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1 G_1}$	$N_{S_2 G_1}$	$N_{S_3 G_1}$
Gate 2	$N_{S_1 G_2}$	$N_{S_2 G_2}$	$N_{S_3 G_2}$
Gate 3	$N_{S_1 G_3}$	$N_{S_2 G_3}$	$N_{S_3 G_3}$
Gate 4		$N_{S_2 G_4}$	$N_{S_3 G_4}$
attenuated	a_1	a_2	a_3
lost to reflection	r_1	r_2	r_3

Table 13

And it holds that $N_{S_1} = N_p (1 - t_1)$

$N_{S_2} = N_{S_1 G_1} (1 - t_2) + N_{S_3 G_1}$

$N_{S_3} = N_{S_2 G_2} (1 - t_3)$

This means that the photons appearing in the first sequence are the propagated ones, reduced by the total percentage of the lost ones. All the photons falling on the first cylinder are provided to the second sequence and they are reduced by the lost percentage. The photons appearing in the second sequence are equal to the remaining ones plus the photons entering again the second sequence through the inner cylinder of the 3rd sequence. All the photons falling on the third cylinder are provided to the 3rd sequence. Then they are reduced by the lost percentage and the remaining photons are detected (appear) at the 3rd sequence.

6th step:

GATE TYPE → GATE for all the surfaces except
Cylinder 1 (that is the cylinder of the 1st sequence)→ TOPGATE
Cylinder 2 (that is the inner cylinder of the 2nd sequence)→ BOTGATE
Cylinder 3 (that is the outer cylinder of the 2nd sequence)→ TOPGATE
Cylinder 4 (that is the inner cylinder of the 3rd sequence)→ BOTGATE

Finally this exercise is to permit the photons to exit the first sequence through its cylinder and enter the second sequence then the photons coming through the outer cylinder of the second sequence to enter the third sequence. At the same time the photons coming through the inner cylinder of the second sequence will return to the first sequence and the photons coming through the inner cylinder of the third sequence will return to the second one. The results are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	1065	196	299
Gate 2	32	1012	598
Gate 3	37	14	1
Gate 4		15	0
attenuated	5.8	2.2	0.2
Lost to reflection	0.4	10.5	11.2

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1 G_1}$	$N_{S_2 G_1}$	$N_{S_3 G_1}$
Gate 2	$N_{S_1 G_2}$	$N_{S_2 G_2}$	$N_{S_3 G_2}$
Gate 3	$N_{S_1 G_3}$	$N_{S_2 G_3}$	$N_{S_3 G_3}$
Gate 4		$N_{S_2 G_4}$	$N_{S_3 G_4}$
attenuated	a_1	a_2	a_3
lost to reflection	r_1	r_2	r_3

Table 14

And it is finally concluded the following relationships are true:

$$\mathbf{N_{S_1} = N_p\,(1 - t_1) + N_{S_2\,G_1}}$$

The number of photons appearing in the 1st sequence is the number of the propagated photons reduced by the corresponding total lost percentage plus the ones coming from the 2nd sequence through its inner cylinder (G_1).

$$\mathbf{N_{S_2} = N_{S_1\,G_1}(1 - t_2) + N_{S_3\,G_1}}$$

The number of photons appearing in the 2nd sequence is the number of the photons entering from the 1st sequence through its cylinder (G_1) reduced by the corresponding total lost percentage plus the number of photons entering from the 3rd sequence through its inner cylinder (G_1).

$$\mathbf{N_{S_3} = N_{S_2\,G_2}(1 - t_3)}$$

The number of photons appearing in the 3rd sequence is the number of photons entering from the 2nd sequence through its outer cylinder (G_2) reduced by the corresponding total lost percentage.

2. Running GuideIt under various configurations

2.1 Still source

In this section, we shall study the contribution of each different parameter of imperfection to the reduction of the amount of photons while traveling in the optical fiber.

A large file of 200,000 events is created assuming that the optical fibers are perfect. That means that the materials of the core and the claddings are perfectly transparent and no absorption occurs. All the surfaces are perfectly reflective and refractive.

A fixed photon source is used to produce the events in the middle of the optical fiber and the simulations are run for 7 different fibre lengths.

That set of files is named *StGeosmooth* since the source is still (St), the only parameter that causes reduction to the photons is the geometry (Geo) and all the surfaces of all sequences 'are' smooth. The following table shows the settings in the input file of GuideIt.

StGeosmooth

Bulk Attenuation	NO
Attenuation Length in Core	-
Attenuation Length in Clads	-
Surface Roughness inside	1
Surface Roughness outside	1
Source	Still
Source Position	In the middle of the fiber
# of propagated photons	200,000
# of random numbers	200
Fibre Length	50, 100, 200, 300, 390, 500, 600

Table 15

This entire job is repeated by adding one imperfection at a time. The first one is the surface roughness. So the set of the created files is named *StGeonosmooth* by following the same way of thinking and here is the parameters set in the input file:

StGeonosmooth

Bulk Attenuation	NO
Attenuation Length in Core	-
Attenuation Length in Clads	-
Surface Roughness inside	0.9999
Surface Roughness outside	0.999
Source	Still
Source Position	In the middle of the fiber
# of propagated photons	200,000
# of random numbers	200
Fiber Length	50, 100, 200, 300, 390, 500, 600

Table 16

Another imperfection of the material of the fiber is that it is not perfectly transparent and as a result an amount of photons are absorbed from the material. The core's attenuation length is set up to 350 cm and for both claddings up to 1200 cm. The attenuation length is defined as the distance into a material when the probability has dropped to 1/e that a photon has not been absorbed. Alternatively, if there is a beam of photons incident on the material, the attenuation length is the distance where the intensity of the beam has dropped to 1/e, or about 63% of the photons have been absorbed.) The same set of files is created including that imperfection. The name of that file is *StAl350_1200smooth*, because the source is still, the attenuation lengths have these values and it is assumed that the roughness imperfection of the surfaces does not exist. The input file parameters are:

StAl350_1200smooth

Bulk Attenuation	YES
Attenuation Length in Core	350
Attenuation Length in Clads	1200
Surface Roughness inside	1
Surface Roughness outside	1
Source	Still
Source Position	In the middle of the fiber
# of propagated photons	200,000
# of random numbers	200
Fiber Length	50, 100, 200, 300, 390, 500, 600

Table 17

Finally a set of files is created taking in account all the imperfections of the fiber. Its name is StAl350_1200nosmooth and the input file contains the following settings:

StAl350_1200nosmooth

Bulk Attenuation	YES
Attenuation Length in Core	350
Attenuation Length in Clads	1200
Surface Roughness inside	0.9999
Surface Roughness outside	0.999
Source	Still
Source Position	In the middle of the fiber
# of propagated photons	200,000
# of random numbers	200
Fiber Length	50, 100, 200, 300, 390, 500, 600

Table 18

After collecting this data it is easy to plot them and to see the relationship of the reduction of photons while traveling in the core and the cladding as a function of their path. At this point we are going to use the mean speed of light e calculated earlier to find the mean photon path for photons, which appear in the first cladding.

Table of results

		StGeosmooth							StGeonosmooth						
		50cm	100cm	200cm	300cm	390cm	500cm	600cm	50cm	100cm	200cm	300cm	390cm	500cm	600cm
Seq.1	G_2	12775	12648	12900	12808	12718	12756	12612	12852	12482	12451	12337	12146	11850	11768
	Tof	1.375	2.768	5.514	8.301	10.780	13.810	16.590	1.375	2.767	5.516	8.3	10.77	13.81	16.58
	S	25.78	51.9	103.39	155.64	202.125	258.94	311.06	25.78	51.88	103.425	155.625	201.94	258.94	310.875
Seq.2	G_3	15438	15660	15311	15407	15537	15491	15235	12931	10929	8124	5979	4535	3379	2634
	Tof	1.375	2.716	5.463	8.215	10.65	13.65	16.40	1.375	2.705	5.445	8.182	10.58	13.54	16.25
	S	25.89	51.14	102.87	154.69	200.54	257.03	308.81	25.89	50.94	102.53	154.07	199.22	254.96	305.99
Seq.3	G_2	11260	11345	11320	11388	11321	11459	11310	1455	367	112	38	22	19	13
	Tof	1.43	2.75	5.447	8.162	10.62	13.61	16.34	1.43	2.75	5.39	8.03	10.45	13.31	15.95
		StAl350_1200smooth							StAl350_1200nosmooth						
		50cm	100cm	200cm	300cm	390cm	500cm	600cm	50cm	100cm	200cm	300cm	390cm	500cm	600cm
Seq.1	G_2	11816	11096	9314	8254	7343	6080	5402	11778	10984	9159	7958	6879	5659	4845
	Tof	1.375	2.769	5.515	8.301	10.77	13.81	16.58	1.375	2.769	5.516	8.297	10.77	13.81	16.57
	S	25.78	51.92	103.41	155.64	201.94	258.94	310.875	25.78	51.92	103.425	155.57	201.94	258.94	310.69
Seq.2	G_3	14697	13805	12643	11647	10768	9797	8716	12487	10111	6693	4364	3140	2054	1457
	Tof	1.375	2.715	5.464	8.214	10.65	13.65	16.39	1.375	2.702	5.442	8.181	10.57	13.53	16.25
	S	25.89	51.78	102.89	154.67	200.54	257.03	308.62	25.89	50.88	102.47	154.05	199.03	254.77	305.99
Seq.3	G_2	11156	10895	10438	9799	9520	9162	8689	1424	400	94	33	25	17	13
	Tof	1.43	2.75	5.448	8.160	10.62	13.61	16.33	1.43	2.75	5.39	8.03	10.45	13.31	15.95

Table 19

$$Seq.1: S = c_{core} \times Tof$$
$$Seq.2: S = \bar{c} \times Tof$$

The next plots summarize the results of the table:

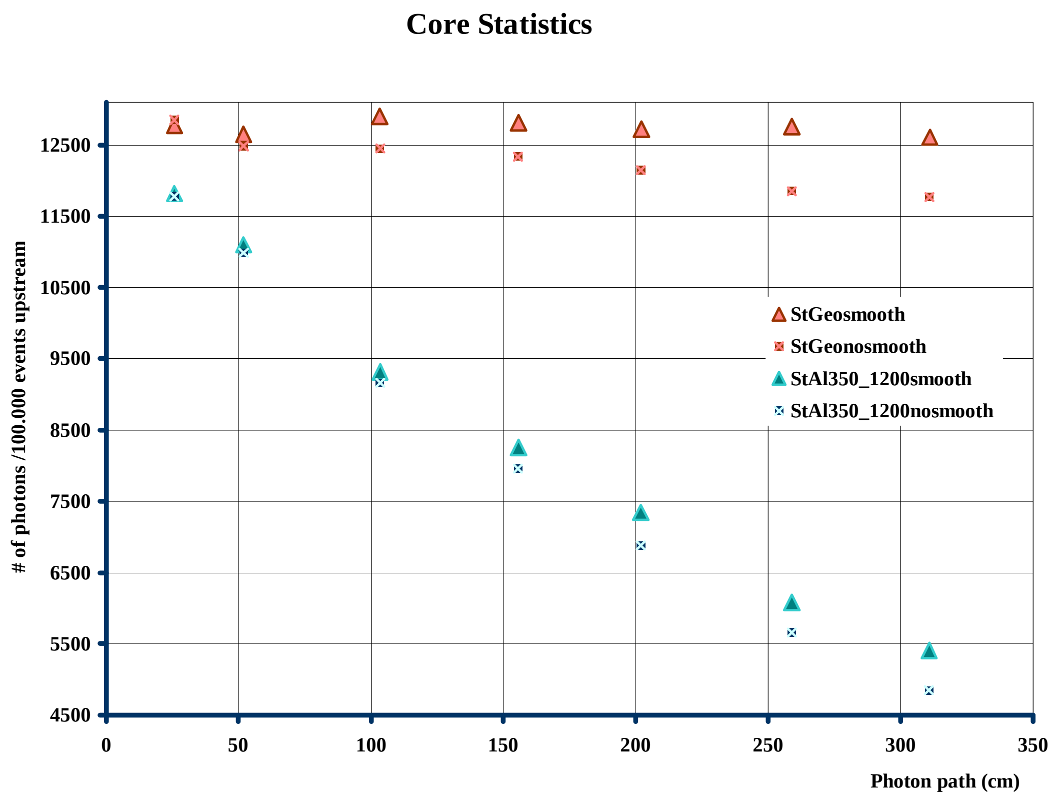


Fig.7:

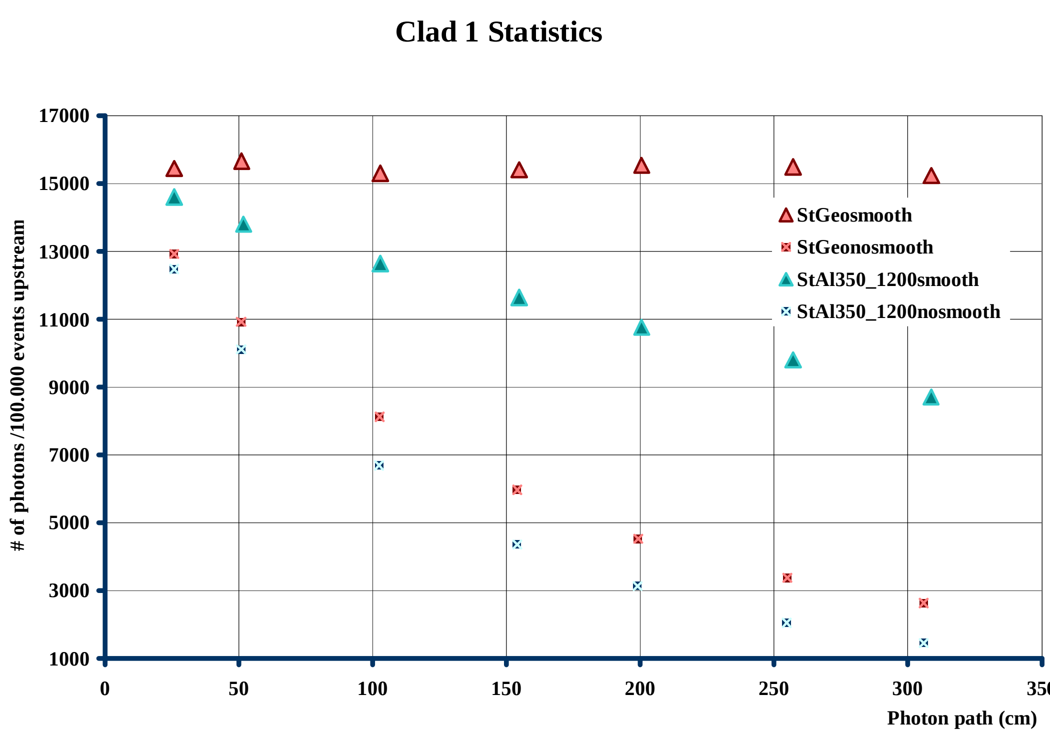


Fig.8:

Identically, while summing the total number of photons ending upstream through the core and the claddings as a function of the length of the fiber one can determine the capture ratio of the optical fiber. So it is very useful to study the following table.

100000 events upstream	50cm	100cm	200cm	300cm	390cm	500cm	600cm
StGeosmooth	39473	39653	39531	39603	39567	39706	39157
StGeonosmooth	27238	23778	20687	18354	16703	15248	14415
StAl350_1200smooth	37669	35796	32395	29700	27631	25039	22807
StAl350_1200nosmooth	25689	21495	15946	12355	10044	7730	6315

Table 20

It should be noticed that the contribution of the claddings is high because the fiber is surrounded by air and no photons escape out of the fifth cylinder due to refraction.

2.2 Fiber in glue with index of refraction n=1,6 (Appendix I)

When a fiber is surrounded by glue it is expected that the behavior of the photons in the 3rd sequence will change. All photons falling on the 5th cylinder should be refracted and no photons will be reflected back because they travel from a lower to a higher index of refraction material. Let's see an example for a fiber surrounded by air and by glue. Here no bulk attenuation and surface roughness have been taken into account since it is important to focus on the results of the glue. A thousand of events are propagated by a still source in the middle of a 390cm long fiber. The fourth cylinder is set as a simple GATE (and not as a BOTGATE) in order to avoid allowing photons passing from the 3rd sequence to the 2nd.

Air around the fiber n=1			
	Sequence 1	Sequence 2	Sequence 3
Gate 1	931	2	245
Gate 2	34	883	594
Gate 3	37	23	22
Gate 4		23	22
Glue around the fiber n=1,6			
	Sequence 1	Sequence 2	Sequence 3
Gate 1	928	3	7
Gate 2	32	875	868
Gate 3	43	21	0
Gate 4		29	0

Table 21

Those out_files are modified as follows if the fourth cylinder is set a BOTGATE and allows the photons to enter from the 3rd to the previous sequences:

Air around the fiber n=1			
	Sequence 1	Sequence 2	Sequence 3
Gate 1	1072	207	319
Gate 2	72	1044	596
Gate 3	63	68	59
Gate 4		72	70
Glue around the fiber n=1,6			
	Sequence 1	Sequence 2	Sequence 3
Gate 1	934	6	10
Gate 2	33	886	876
Gate 3	39	26	0
Gate 4		26	0

Table 22

It can be obviously concluded that the reason of all the changes in the sequences 1 and 2 is the different way that the photons are distributed in the 3rd sequence according to the surrounding material.

Now that the behavior of the fiber is well understood, we repeat the study that was presented at the previous chapter (how each different parameter of imperfection contributes to the reduction of the photons while traveling in the optic fiber).
The same kind of files is created and they are given the same names with the addition of the capital G (to signify the glue around the fiber) in order as to be distinguished from the former ones.

	GStGeoSmooth	*GStGeonoSmooth*	*GStAlSmooth*	*GStAlnoSmooth*
Bulk Attenuation	NO	NO	YES	YES
Attenuation Length in Core	-	-	350	350
Attenuation Length in Clads	-	-	1200	1200
Surface Roughness inside	1	0.9999	1	0.9999
Surface Roughness outside	1	0.999	1	0.999
Source	Still	Still	Still	Still
Source Position	In the middle of the fiber	In the middle of the fiber	In the middle of the fiber	In the middle of the fiber
# of propagated photons	200,000	200,000	200,000	200,000
# of random numbers	200	200	200	200
Fiber Length (cm)	50, 100, 200, 300, 390, 500, 600	50, 100, 200, 300, 390, 500, 600	50, 100, 200, 300, 390, 500, 600	50, 100, 200, 300, 390, 500, 600

Table 23

The results are summarized at the following tables:

Table of results

		GStGeoSmooth							GStGeonoSmooth						
		50cm	100cm	200cm	300cm	390cm	500cm	600cm	50cm	100cm	200cm	300cm	390cm	500cm	600cm
Seq.1	G_2	7031	7008	7094	7221	6957	7004	7033	7076	6976	6838	6988	6642	6577	6548
	Tof	1.375	2.764	5.514	8.3	10.77	13.810	16.57	1.375	2.763	5.512	8.297	10.77	13.81	16.57
	S	25.78	51.825	103.39	155.625	201.94	258.94	310.69	25.78	51.81	103.35	155.57	201.94	258.94	310.69
Seq.2	G_3	4577	4575	4570	4563	4597	4614	4614	3954	3263	2322	1790	1343	1011	793
	Tof	1.375	2.713	5.465	8.215	10.65	13.65	16.39	1.375	2.70	5.444	8.187	10.58	13.54	16.25
	S	25.89	51.08	102.90	154.69	200.54	257.03	308.62	25.89	50.84	102.51	154.16	199.22	254.96	305.99
Seq.3	G_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tof	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		GStAl350_1200Smooth							GStAl350_1200noSmooth						
		50cm	100cm	200cm	300cm	390cm	500cm	600cm	50cm	100cm	200cm	300cm	390cm	500cm	600cm
Seq.1	G_2	6577	6018	5280	4571	3946	3361	2903	6489	5973	5196	4378	3876	3137	2708
	Tof	1.375	2.764	5.512	8.303	10.77	13.81	16.58	1.375	2.762	5.511	8.300	10.77	13.80	16.58
	S	25.78	51.825	103.35	155.68	201.94	258.94	310.875	25.78	51.79	103.33	155.625	201.94	258.75	310.875
Seq.2	G_3	4428	4182	3821	3485	3234	2849	2585	3720	3049	2102	1307	894	622	444
	Tof	1.375	2.714	5.463	8.217	10.65	13.65	16.39	1.375	2.701	5.441	8.183	10.56	13.54	16.25
	S	25.89	51.10	102.86	154.72	200.54	257.03	308.62	25.89	50.86	102.45	154.08	198.84	254.96	305.99
Seq.3	G_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tof	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 24

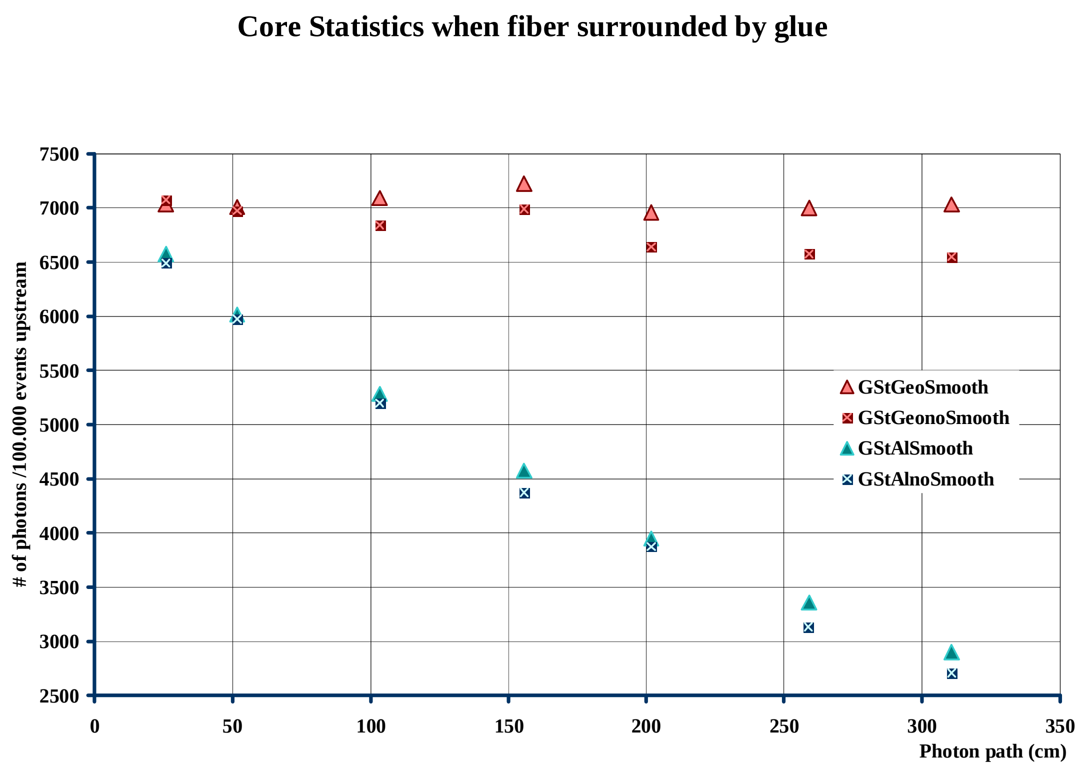

Core Statistics when fiber surrounded by glue
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
# of photons /100.000 events upstream
0
50
100
150
200
250
300
350
Photon path (cm)
GStGeoSmooth
GStGeonoSmooth
GStAlSmooth
GStAlnoSmooth

Fig.10:

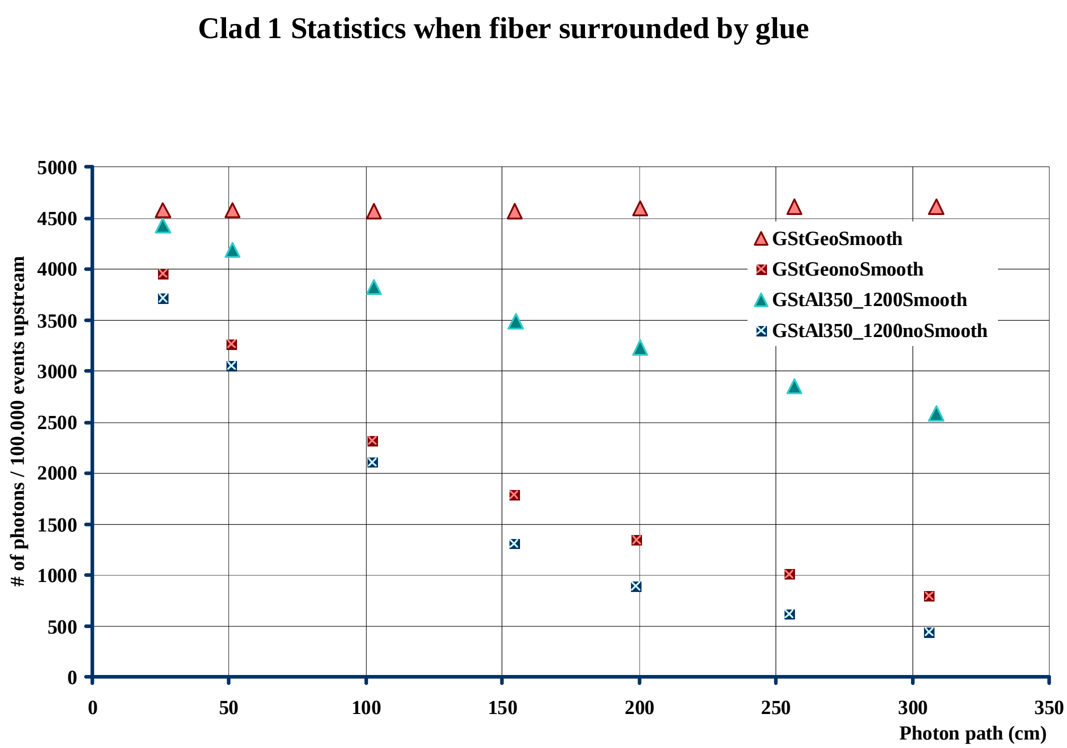

Clad 1 Statistics when fiber surrounded by glue
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
# of photons / 100.000 events upstream
0
50
100
150
200
250
300
350
Photon path (cm)
GStGeoSmooth
GStGeonoSmooth
GStAl350_1200Smooth
GStAl350_1200noSmooth

Fig.11:

The total amount of photons ending upstream through the core and the 1st cladding (since the 2nd one contributes no photons) as a function of the length of the fiber is given in the following table.

100000 events upstream	50cm	100cm	200cm	300cm	390cm	500cm	600cm
GStGeoSmooth	11608	11583	11664	11784	11554	11618	11647
GStGeonoSmooth	11030	10239	9160	8778	7985	7588	7341
GStAl350_1200Smooth	11005	10200	9101	8056	7180	6210	5488
GStAl350_1200noSmooth	10209	9022	7298	5685	4770	3759	3152

Table 25

At the following plots it is easy to compare the core statistics and the clad1 statistics for the realistic runs in both cases, when there is glue around the fiber and when there is not.

It is easily observed that the difference of the number of the captured photons upstream is decreasing as the length of the fiber increases although it is not theoretically expected.

Core Statistics for realistic run with and without glue around the fiber

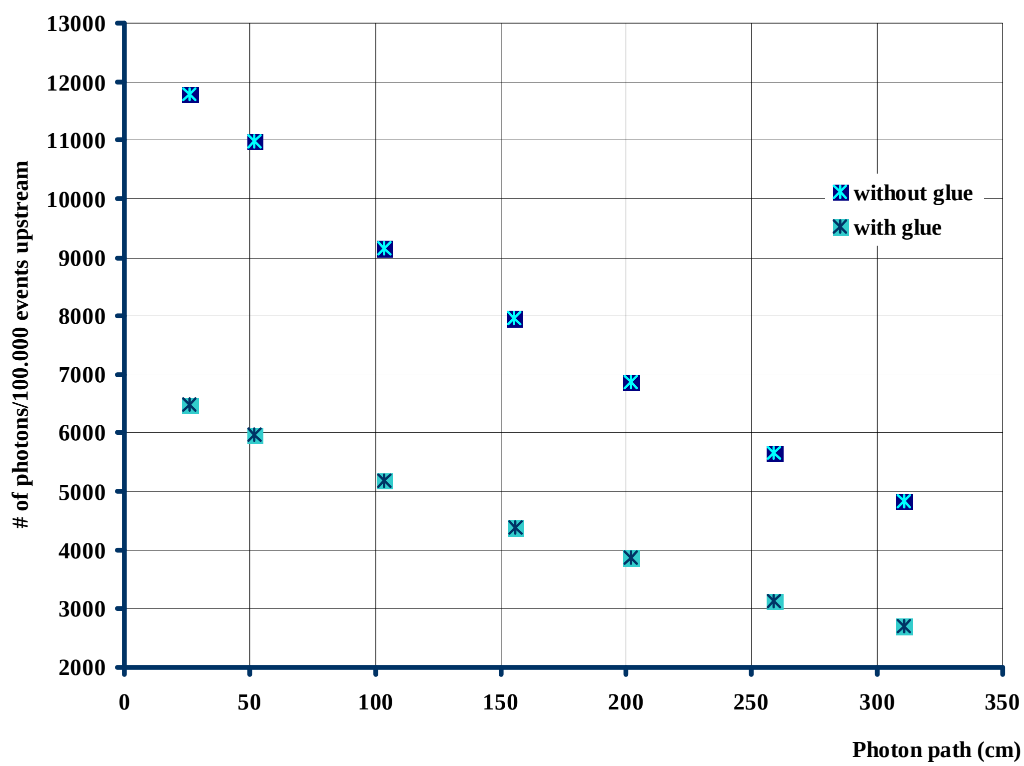


Fig.12:

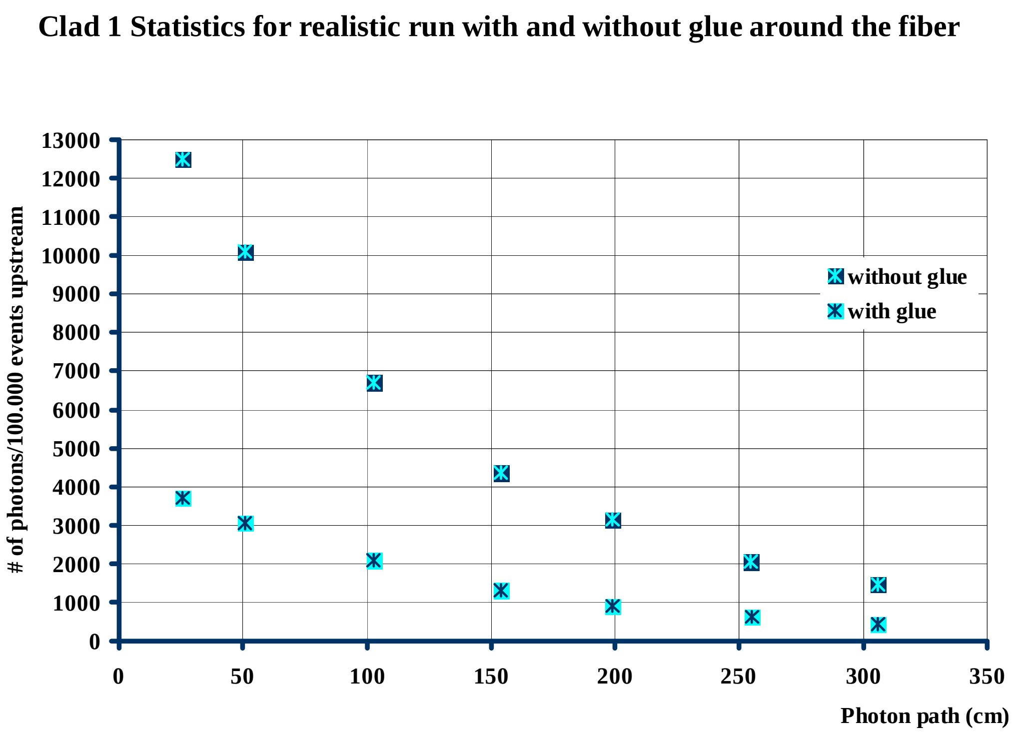


Fig.13:

2.3 Smeared source (Appendix II)

Guideit allows the user to smear the photon source in x, y and z coordinates. The formulae, which give the position of the source, are:

$$x_{source} = x_{start} \pm \frac{x_{smear}}{2}\ ,\ y_{source} = y_{start} \pm \frac{y_{smear}}{2},\ z_{source} = z_{start} \pm \frac{z_{smear}}{2}$$

where x_{start}, y_{start}, z_{start} are the coordinates of the position of the source and x_{smear}, y_{smear}, z_{smear} are the smearing of each of them. In this study only the x and y smearing were used and they were both set equal.

Study for the lost percentages to hole and to maximum bounces

When a run is made with a smearing source, the percentages of missed photons are written in out_file. We lose photons due to 'holes' and due to the maximum bounces (since the maximum number of bounces that is allowed for a photon is set in the input file).

Twelve runs were made with low statistic to take an idea of the behaviour of the fibre while the source smears randomly around the middle of the fibre and always being inside the core.

Smear (cm)	0.06	0.066	0.07	0.074	0.076	0.078	0.08	0.082	0.084	0.086	0.088	0.09
% lost to hole in S_1	0	0.1	0.5	1.9	3	3.6	5.8	6.3	8.8	8.1	11.3	12

Table 26

It is observed that no photons are lost to hole in sequences 2 and 3.

	Smear	0.06	0.066	0.07	0.074	0.076	0.078	0.08	0.082	0.084	0.086	0.088	0.09
% lost to max bounces	S_1	0.3	0.1	0.2	0.5	0.5	0.8	0	0.3	0.1	0.1	0.4	0.1
	S_2	0.1	0.2	0.9	0.7	0	0.9	0.8	0.5	0.5	0.8	0.4	0.9
	S_3	0.5	2.1	2.4	1.7	2.3	2.8	2.3	3.1	3.5	3.4	3	2.8

Table 27

It should be noticed that these percentages refer to the number of photons entering each sequence and not to the initial number of propagated photons.

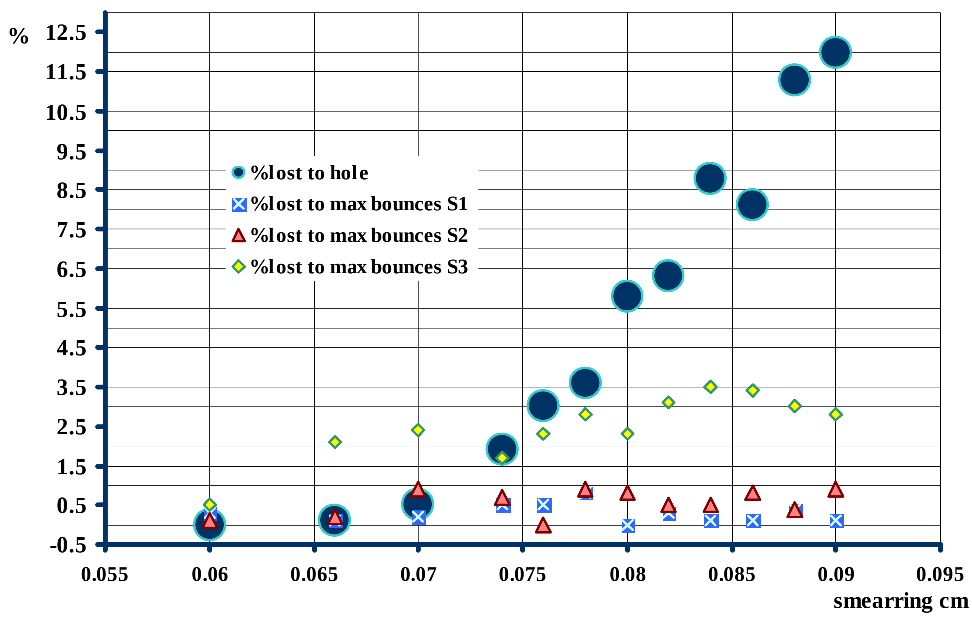


Fig.14: Percentage of photons lost to 'holes' and due to exceeding the maximum number of bounces.

1 'Holes' represent photons, which fail all criteria defined by the user, and they belong to no sequence or gate.

The same kind of study that was presented before for (how each different parameter of imperfection contributes to the reduction of the photons while traveling in the optic fiber) is repeated here using **glue** around the optic fiber and a **randomly smeared source**.

The same kind of files is created and they are given the same names but in a simpler way just to signify whether the attenuation length and the roughness are taken in account or not.

	GeoSmooth	*GeoNosmooth*	*AlSmooth*	*AlNosmooth*
Bulk Attenuation	NO	NO	YES	YES
Attenuation Length in Core	-	-	350	350
Attenuation Length in Clads	-	-	1200	1200
Surface Roughness inside	1	0.9999	1	0.9999
Surface Roughness outside	1	0.999	1	0.999
Source	0.092 smearing	0.092 smearing	0.092 smearing	0.092 smearing
Source Position	In the middle of the fiber	In the middle of the fiber	In the middle of the fiber	In the middle of the fiber
# of propagated photons	200,000	200,000	200,000	200,000
# of random numbers	200	200	200	200
Fiber Length (cm)	50, 100, 200, 300, 390, 500, 600	50, 100, 200, 300, 390, 500, 600	50, 100, 200, 300, 390, 500, 600	50, 100, 200, 300, 390, 500, 600

Table 28

The results are summarized to the following table

Table of results

		Geosmooth							GeoNosmooth						
		50cm	100cm	200cm	300cm	390cm	500cm	600cm	50cm	100cm	200cm	300cm	390cm	500cm	600cm
Seq.1	G_2	12498	12758	12526	12528	12249	12460	12369	11577	11356	10514	9806	9335	8773	8542
	Tof	2.064	3.715	6.832	9.686	12.21	15.1	17.7	1.781	3.311	6.217	9.081	11.6	14.65	17.31
	S	38.7	69.66	128.1	181.6	228.94	283.125	331.875	33.4	62.08	116.57	170.27	217.5	274.69	324.56
Seq.2	G_3	4868	4786	4608	4961	4710	4743	4695	3869	3291	2332	1686	1251	906	667
	Tof	1.494	2.992	5.933	8.912	11.51	14.73	17.5	1.476	2.951	5.835	8.708	11.25	14.28	16.96
	S	28.131	56.34	111.7	167.806	216.725	277.36	329.5	27.792	55.565	109.869	163.965	211.829	268.882	312.344
		Alsmooth							Alnosmooth						
		50cm	100cm	200cm	300cm	390cm	500cm	600cm	50cm	100cm	200cm	300cm	390cm	500cm	600cm
Seq.1	G_2	11474	10316	8748	7229	6236	5162	4386	10685	9449	7413	6108	5180	4153	3364
	Tof	1.878	3.499	6.448	9.383	11.86	14.83	17.51	1.699	3.214	6.092	8.927	11.41	14.47	17.22
	S	35.2	65.61	120.9	175.93	222.4	278.1	328.3	31.86	60.26	114.225	167.38	213.94	271.3	322.9
Seq.2	G_3	4393	4143	3828	3501	3134	2838	2558	3701	2841	1942	1234	877	558	370
	Tof	1.5	2.996	5.915	8.895	11.47	14.6	17.45	1.482	2.927	5.833	8.699	11.19	14.32	17.05
	S	28.244	56.4	111.4	167.49	215.97	274.91	328.57	27.9	55.113	109.8	163.8	210.7	269.635	321.04

Table 29

Core Statistics when fiber surrounded by glue and the source is smearing randomly in the middle of the fiber

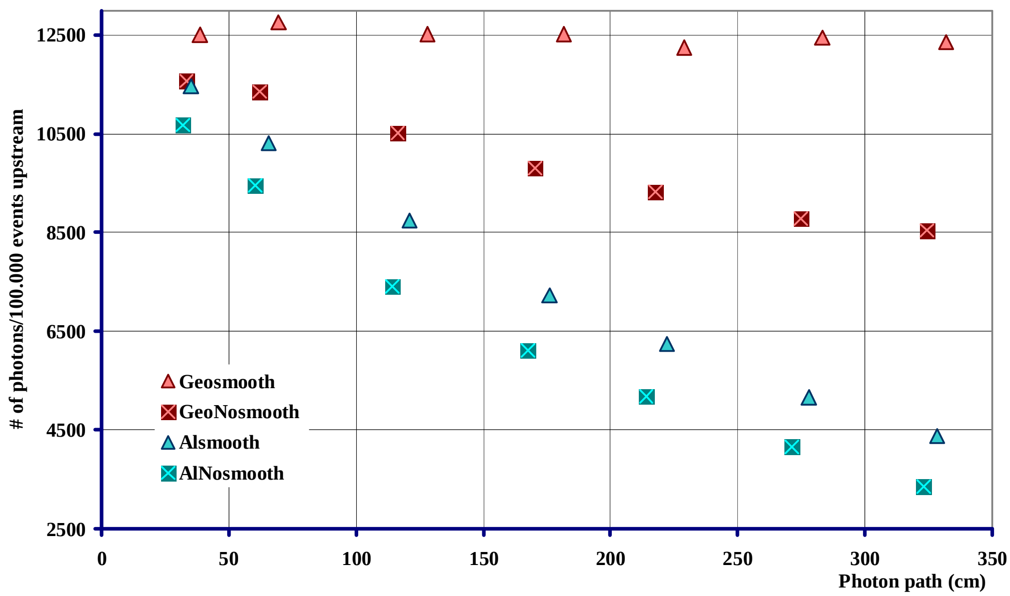


Fig.15:

Clad1 Statistics when fiber surrounded by glue and the source is smearing randomly in the middle of the fiber

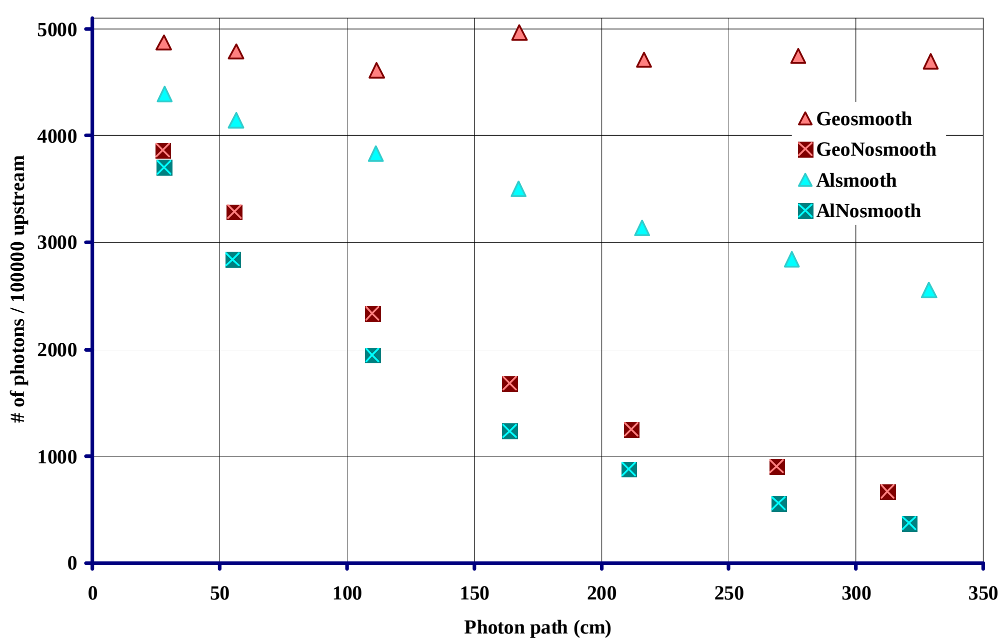


Fig.16:

The total amount of photons ending upstream through the core and the 1st cladding (since the 2nd one contributes no photons) as a function of the length of the fiber is given in the following table.

100000 events upstream	50cm	100cm	200cm	300cm	390cm	500cm	600cm
GeoSmooth	17366	17544	17134	17489	16959	17203	17064
GeoNosmooth	15446	14647	12846	11492	10586	9679	9209
Alsmooth	15867	14459	12576	10730	9370	8000	6944
AlNosmooth	14386	12290	9355	7342	6057	4711	3734

Table 30

At the following plots it is easy to compare the core statistics and the clad1 statistics for the realistic runs when there is glue around the fiber in both cases, and when the source is still and when it is smearing.
It is important to observe here that the difference of the number of the captured photons upstream is decreasing as the length of the fiber increases although it is not theoretically expected only in Figure 17. This problem disappears at the Figure 18!

Core Statistics for realistic run with glue around the fiber for still and smeared source

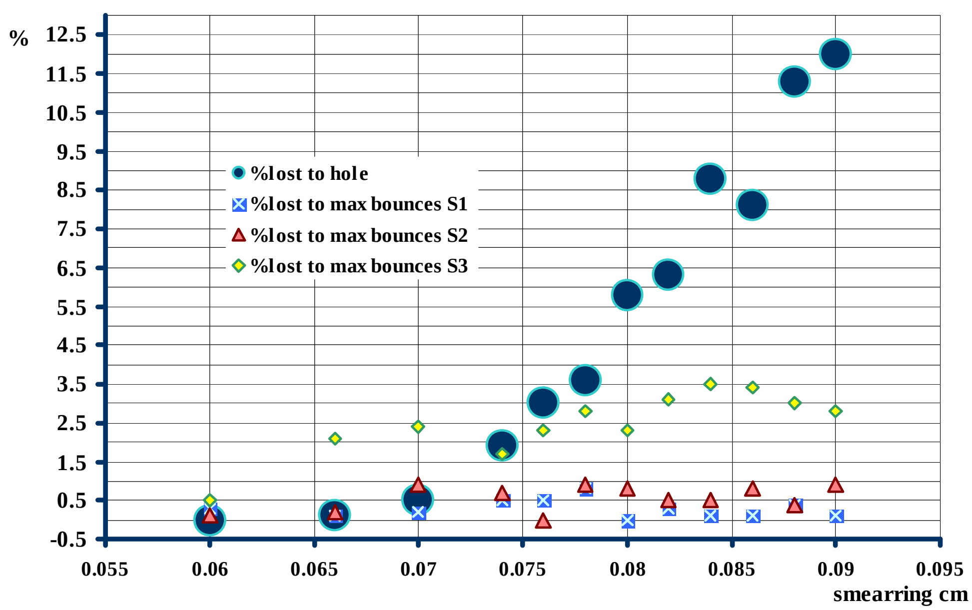


Fig.17:

Clad 1 Statistics for realistic run with glue around the fiber for still and smeared source

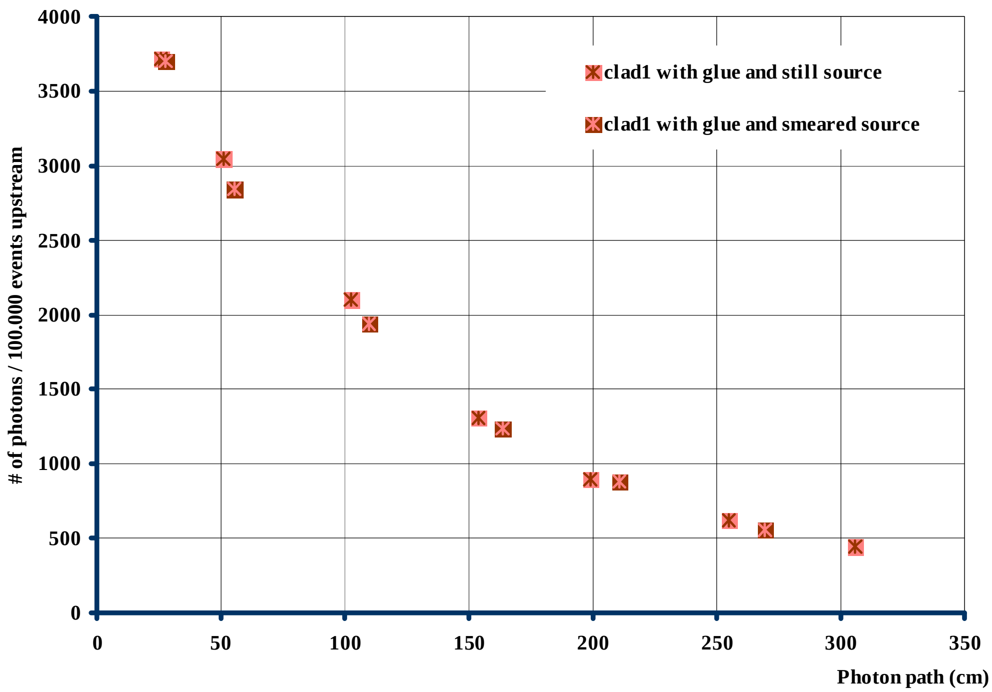


Fig.18:

How many photons come out from the fiber ? Comparison with bibliografia

100000 photons upstream		Fiber length						
		50cm	100cm	200cm	300cm	390cm	500cm	600cm
Total amount of photons coming out of the fiber (realistic run)	Still source air	25689	21495	15946	12355	10044	7730	6315
	Still source glue	10209	9022	7298	5685	4770	3759	3152
	Smeared source glue	14386	12290	9355	7342	6057	4711	3734

Table 30

The following plot summarizes the upstream captured percentage of photons for a 390cm long fiber and a still source in the middle of it, in all cases with air and glue outside when the source is fixed and with glue outside when the source is smearing.

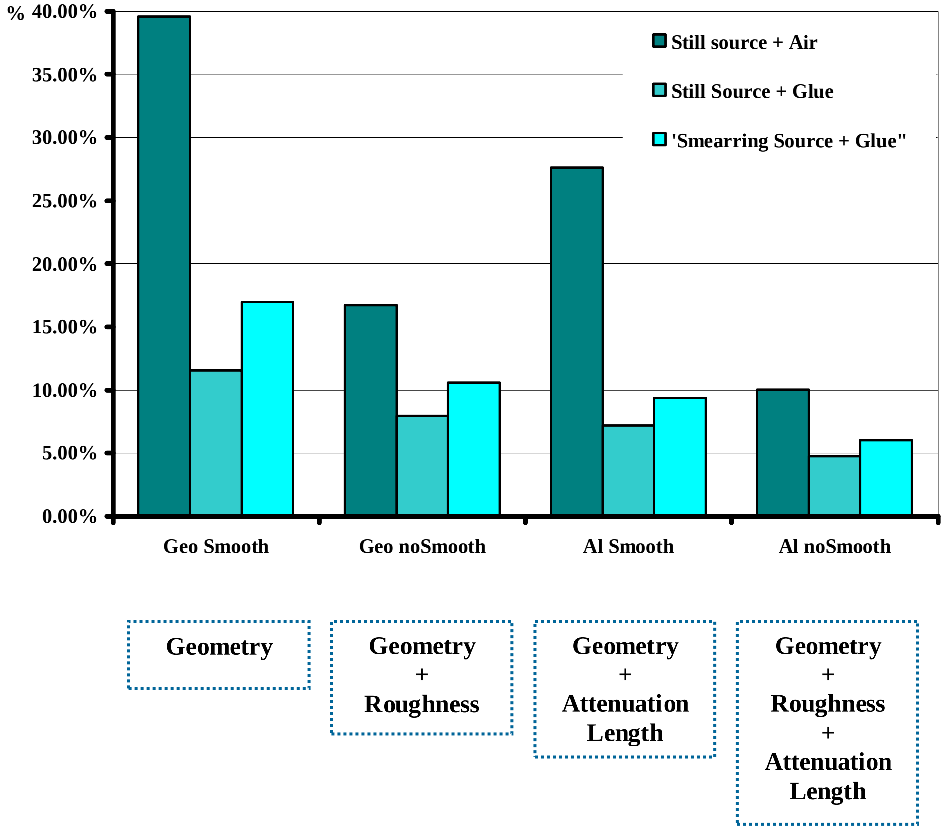


Fig.19: Capture percentages of photons

But there is something wrong!

At this point what will convince everybody that there is something wrong (and that is the IOR settings) is a quick look at a diagnostic tracking output!
That what happens is that all the photons, which enter the first cladding, are trapped there and never enter the core again! This violates Snell's Law! No total reflections are allowed to take place on the internal cylinder of the 1st cladding and a photon could never be trapped in the first cladding! That's why there is always an unexpectedly high number of photons coming out from clad 1.

That was the main reason, which made us go on to the second part of our study.

SECOND PART

1. Running GuideIt under the most realistic configuration (Appendix III)

The ***most realistic*** study that was presented before (for how each different parameter of imperfection contributes to the reduction of the photons while traveling in the optic fiber) is repeated here using **glue** around the optic fiber, a **randomly smeared source** and of course **IORs** as are shown in Table 2.

The same kind of files are created and they are given the same names but in a simpler way just to signify whether the attenuation length and the roughness are taken in account or not.

	AlNosmooth
Bulk Attenuation	YES
Attenuation Length in Core	350
Attenuation Length in Clads	1200
Surface Roughness inside	0.9999
Surface Roughness outside	0.999
Source	0.092 smearing
Source Position	In the middle of the fiber
# of propagated photons	200,000
# of random numbers	200
Fiber Length (cm)	50, 100, 200, 300, 390, 500, 600

Table 31

The results are summarized in the following table:

Table of results

	IOR AlNosmooth							
		50cm	100cm	200cm	300cm	390cm	500cm	600cm
Seq.1	G_2	13899	12362	9869	8099	6753	5490	4551
	Tof	1.649	3.181	6.096	9.011	11.56	14.68	17.46
	S	30.92	59.64	114.3	168.96	216.75	275.25	327.38
Seq.2	G_3	771	739	601	452	400	338	247
	Tof	1.578	3.181	6.353	9.36	12.17	15.67	18.36
	S	29.71	59.90	119.63	176.25	229.16	295.07	345.72

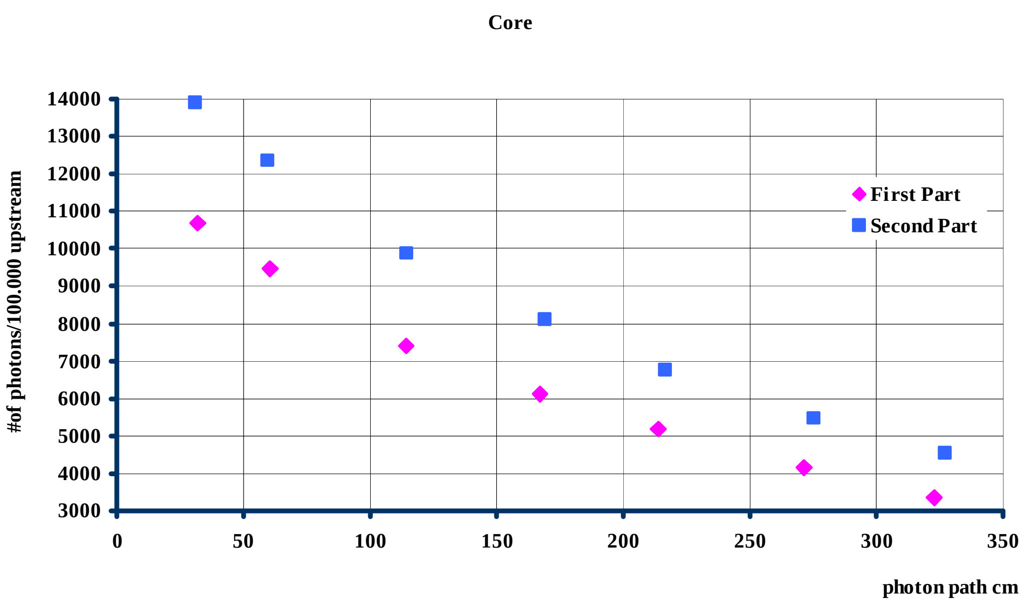
Table 32

Before plotting my results I decided at the same time to compare them with the corresponding configuration of the First Part, but after recalculating the mean photon path in the 2nd sequence using the speed of light for the 1st cladding ($c_1 = 20.134\, cm/ns$) since the photons travel only there.

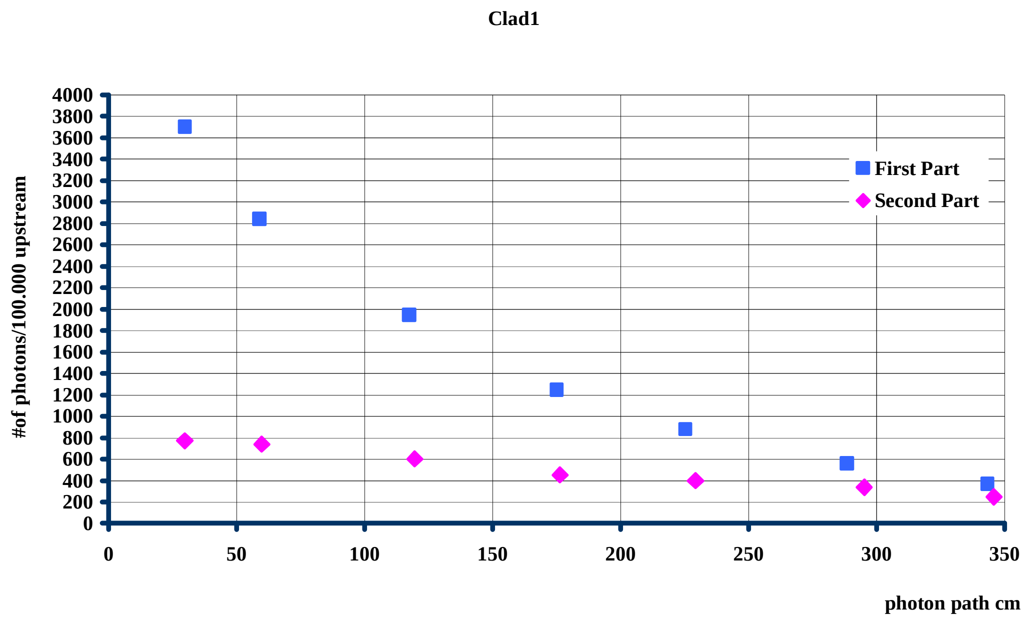
	Alnosmooth							
		50cm	100cm	200cm	300cm	390cm	500cm	600cm
Seq.1	G_2	10685	9449	7413	6108	5180	4153	3364
	Tof	1.699	3.214	6.092	8.927	11.41	14.47	17.22
	S	31.86	60.26	114.23	167.38	213.94	271.31	322.88
Seq.2	G_3	3701	2841	1942	1234	877	558	370
	Tof	1.482	2.927	5.833	8.699	11.19	14.32	17.05
	S	29.84	58.93	117.44	175.15	225.30	288.32	343.28

Table 33

Comparison of Core Statistics when fiber surrounded by glue and the source is smearing randomly in the middle of the fiber

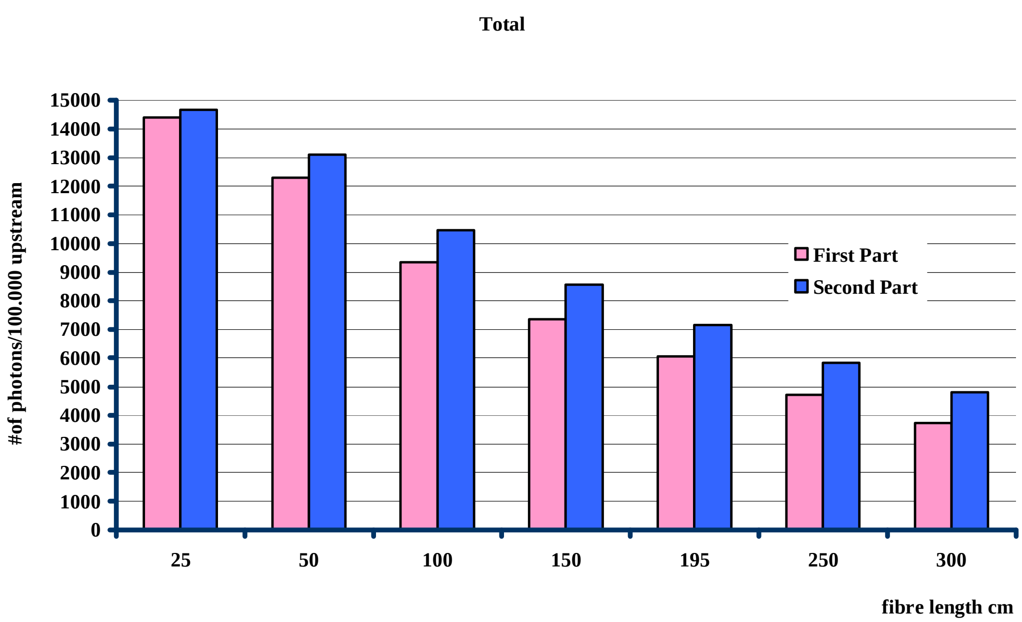


Obviously more photons appear in core since most of photons, which are trapped due to 1st cladding exit from the core. Below we see the expected reduction of the photons appearing in the 1st cladding.



Another very important observation is that the discrepancy that occurred in the First Part (*the difference of the number of the captured photons upstream is decreasing as the length of the fiber increases although it is not theoretically expected)* does not occur at the second part. The number of the captured photons follows the exponential fall due to the attenuation length of the material of the fiber.

Finally the next plot compares the total captured amount of photons in both cases.



From that very last plot we can come to some conclusions. We are interested in the total capture ability of the optic fibre we are simulating and not in the partial fraction of photons (captured due to core and due to clad 1). In the Second Part the captured percentage of photons is ~1% higher than the one in the First Part. On the other hand the behaviour of the photons in the optic fibre is closer to reality. That is something, which is expected or demanded.

What about the bounces in the 1st cladding?

Unfortunately we still observe a strange behavior. A look at the diagnostic tracking output shows that there is a great improvement but still we have few anomalies. Another thing that should be checked is the number of bounces on both cylinders of the 1st cladding. In the First Part the number of bounces on the inside cylinder is always almost equal to the number of bounces on the outside cylinder. On the contrary, in the Second Part the number of bounces on the inside cylinder of clad 1 is ~5 times less than the number of bounces on the outside cylinder. Those bounces occur with no reason when a photon is traveling in the expected way through clad 1 and core. This indicates that there may really made be a bug somewhere in the code of GuideIt.

2. Number of photons booked at each gate and Number of bounces

Lastly I will present the way that relates the number of bounces at each surface and the number of photons that are booked from each gate. Fortunately things are much more simple here!

Lets have a look to the output file of an **Ideal Simulation:**

As a first attempt the BULK ATTENUATION option is set to NO, the option of the SURFACE ROUGHNESS is set to 1 for all surfaces and the source is still in order to avoid any lost percentage of photons. The number of generated photons is 1000.

	Sequence 1	Sequence 2	Sequence 3
Gate 1	35147	34256	18
Gate 2	48	906	888
Gate 3	61	1	0
Gate 4	-	2	0
#of bounces	G_1: 42873	G_1: 5723	G_1:6
#of bounces	-	G_2: 39962	G_2:24

Using the following symbols to represent the number of photons appearing at each gate and sequence.

N_p : propagated number of photons

$N_{S_i G_j}$: number of photons booked from the G_j Gate of the S_i Sequence

i=1,2,3 (since we have 3 sequences)
j=1,2,3 for the 1st sequence (since it is consisted by 3 surfaces that is 3 gates)
j=1,2,3,4 for the 2nd and the 3rd sequence (since they are composed of 4 surfaces that is 4 gates)
We can also symbolize the number of bounces at a gate of a sequence with the “B”.
The former example of the table can take a more general expression:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1\,G_1}$	$N_{S_2\,G_1}$	$N_{S_3\,G_1}$
Gate 2	$N_{S_1\,G_2}$	$N_{S_2\,G_2}$	$N_{S_3\,G_2}$
Gate 3	$N_{S_1\,G_3}$	$N_{S_2\,G_3}$	$N_{S_3\,G_3}$
Gate 4		$N_{S_2\,G_4}$	$N_{S_3\,G_4}$
#of bounces	$B_{S_1\,G_1}$	$B_{S_2\,G_1}$	$B_{S_3\,G_1}$
#of bounces		$B_{S_2\,G_2}$	$B_{S_3\,G_2}$

Table 33

$\mathbf{N_{S_1\,G_1} = [N_{produced} - N_{S_1\,G_2} - N_{S_1\,G_3}] + N_{S_2\,G_1}}$: Is the number of passages of photons through this gate (cylinder of core) to the next sequence (clad 1)

$\mathbf{N_{S_2\,G_1} = B_{S_2\,G_2} - B_{S_2\,G_1}}$: Is the number of passages of photons through this gate (inside cylinder of clad 1) to the previous sequence (core)

$\mathbf{N_{S_2\,G_2} = N_{S_3\,G_1} + N_{S_3\,G_2}}$: Is the number the number of photons passing through this gate (outside cylinder of clad1) to the next sequence (clad 2)

$\mathbf{N_{S_3\,G_1} = B_{S_3\,G_2} - B_{S_3\,G_1}}$: Is the number of passages of photons through this gate (inside cylinder of clad 2) to the previous sequence (clad 1)
Notice that all numbers of the last relationship should be 0 since no total reflection is allowed on any surface of the 3rd sequence! Fortunately the number of this anomaly is extremely small that can be neglected.

Finally the number of produced photons is equal to the number of photons exiting the fibre from the gates leading to the area out of it.
$\mathbf{N_{produced} = N_{S_1\,G_2} + N_{S_1\,G_3} + N_{S_2\,G_3} + N_{S_2\,G_4} + N_{S_3\,G_2} + N_{S_3\,G_3} + N_{S_3\,G_4}}$

Now let us look at the output file of the **Realistic Simulation:**

The option of BULK ATTENUATION is set to YES and the attenuation lengths are set to 350cm for the core and 1200cm for the claddings.[1]
In addition, the option of the SURFACE ROUGHNESS is set to 0.9999 for all the surfaces inside the fibre and 0.999 for the external surface, specifically the cylinder 5 or in other words the outer cylinder of the 3rd sequence, following the recommendation of the GuideIt manual.
Lets introduce in advance the notation (as it concerns the percentages of photons lost due to various reasons) that is going to be used in the following steps.
a_i% is the percentage of photons that are attenuated in the i sequence

r_i% is the percentage of photons that are lost due to reflection on a rough surface in the i sequence
h_i% is the percentage of photons that are lost to a hole in the i sequence and
$t_i\% = a_i\% + r_i\% + h_i\%$ is the total percentage of photons that is lost in the i sequence i=1,2,3

The results we receive at the out_file are:

	Sequence 1	Sequence 2	Sequence 3
Gate 1	27022	26330	16
Gate 2	37	706	689
Gate 3	31	1	0
Gate 4	-	0	0
attenuated	7.7	0.1	0
lost to a hole	13.5	0	0
#of bounces	G_1: 263019	G_1: 5971	0
lost to reflection	2.8	0	0
#of bounces	-	G_2: 32286	G_2: 17
lost to reflection	-	0.1	0

	Sequence 1	Sequence 2	Sequence 3
Gate 1	$N_{S_1\,G_1}$	$N_{S_2\,G_1}$	$N_{S_3\,G_1}$
Gate 2	$N_{S_1\,G_2}$	$N_{S_2\,G_2}$	$N_{S_3\,G_2}$
Gate 3	$N_{S_1\,G_3}$	$N_{S_2\,G_3}$	$N_{S_3\,G_3}$
Gate 4	-	$N_{S_2\,G_4}$	$N_{S_3\,G_4}$
attenuated	a_1	a_2	a_3
lost to a hole	h_1	h_2	h_3
#of bounces	$B_{S_1\,G_1}$	$B_{S_2\,G_1}$	$B_{S_3\,G_1}$
lost to reflection	r_1	r_{21}	r_{31}
#of bounces	-	$B_{S_2\,G_2}$	$B_{S_3\,G_2}$
lost to reflection	-	r_{22}	r_{32}

Table 34

$N_{S_1\,G_1} = [N_{produced}\,(1-t_1) - N_{S_1\,G_2} - N_{S_1\,G_3}] + N_{S_2\,G_1}$: Is the number of passages of photons through this gate (cylinder of core) to the next sequence (clad 1)

$N_{S_2\,G_1} = B_{S_2\,G_2} - B_{S_2\,G_1}$: Is the number of passages of photons through this gate (inside cylinder of clad 1) to the previous sequence (core)

$N_{S_2\,G_2} = N_{S_3\,G_1} + N_{S_3\,G_2}$: Is the number of photons passing through this gate (outside cylinder of clad1) to the next sequence (clad 2)

$N_{S_3\,G_1} = B_{S_3\,G_2} - B_{S_3\,G_1}$: Is the number of passages of photons through this gate (inside cylinder of clad 2) to the previous sequence (clad 1)
Notify that all numbers of the last relationship should be 0 since no total reflection is allowed on any surface of the 3rd sequence! **Fortunately the number of this anomaly is extremely small that can be neglected.**

Finally the number of produced photons is equal to the number of photons exiting the fibre from the gates leading to the area out of it.

$$N_{produced}\,[1-(t_1+t_2)] = N_{S_1 G_2} + N_{S_1 G_3} + N_{S_2 G_3} + N_{S_2 G_4} + N_{S_3 G_2} + N_{S_3 G_3} + N_{S_3 G_4}$$

Conclusions

After that part of the study I can say that the running configuration of the Second Part is revealing a GuideIt with a more "reasonable way of thinking" and with fewer violations of physics laws.

Acknowledgements

I want to thank alphabetically:
Dr. Ioannou Pavlos, National and Kapodistrian University of Athens, Hellas
Dr. Kourkoumelis Christina, National and Kapodistrian University of Athens, Hellas
Dr. Lolos George, University of Regina, SK Canada
Dr. Papandreou Zisis, University of Regina, SK Canada

References

[1] **http://www.detectors.saint-gobain.com/**
SGC Scintillating Optical Fibers Brochure 605.pdf

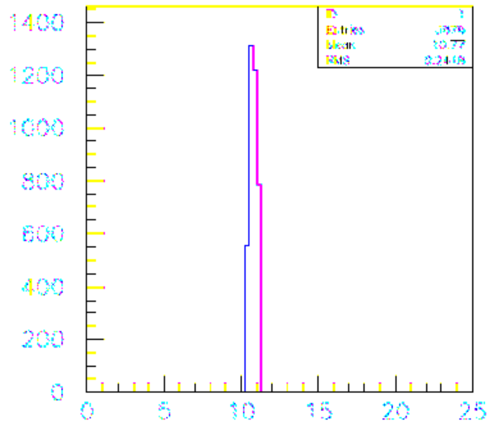
[2] **GuideIt Manual**

[3] **R.Ziegler, "Investigation of the GuideIt Ray Tracing Program", GlueX-doc-649 (2004)**

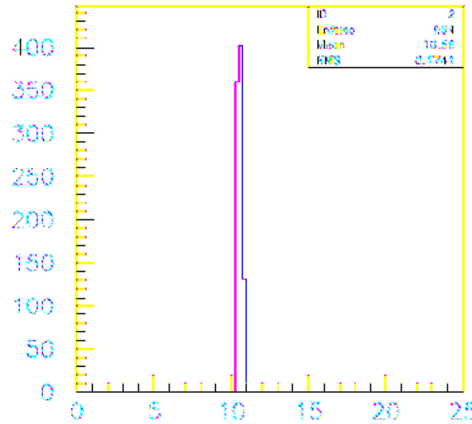
[4] **nakonechy**

Appendix I

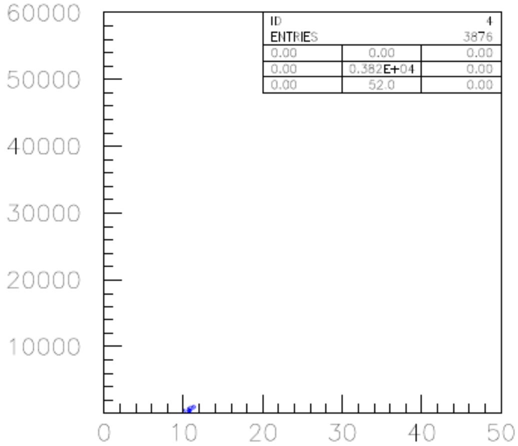
Still Source, Attenuation Length and Surface Roughness included, Glue around the fiber



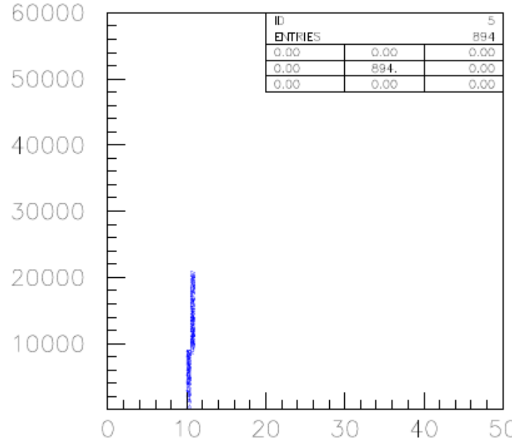
Upstream Tof Seq.1



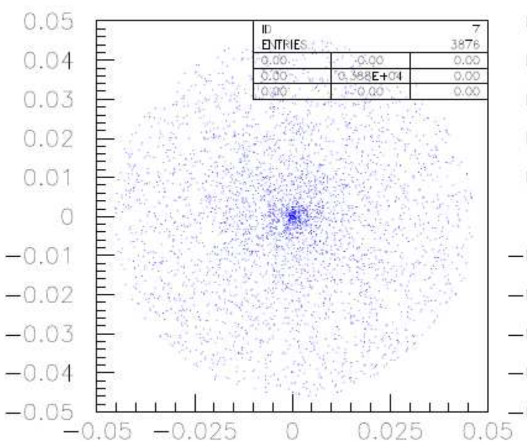
Upstream Tof Seq.2

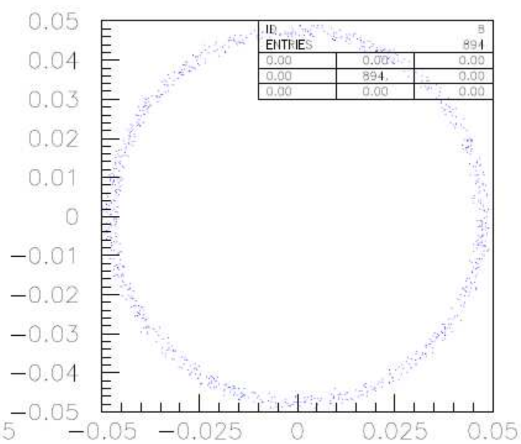


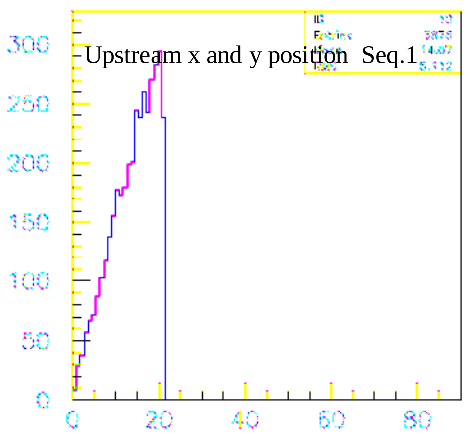
Upstream bounces vs Tof Seq.1

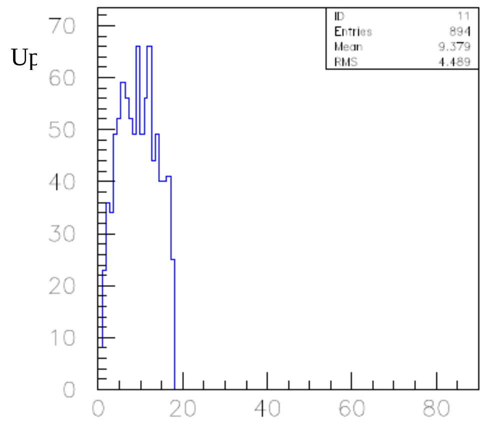


Upstream bounces vs Tof Seq.2







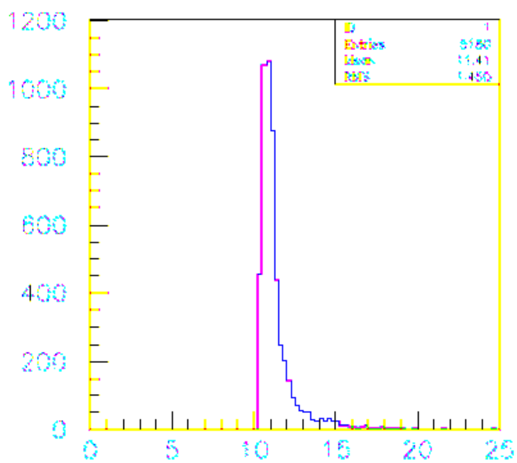


Upstream exit theta Seq.1

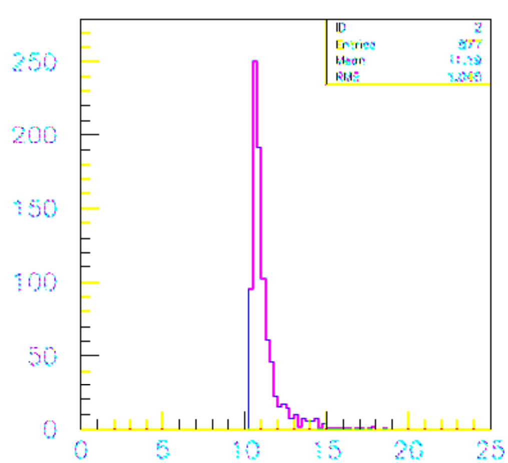
Upstream exit theta Seq.2

Appendix II

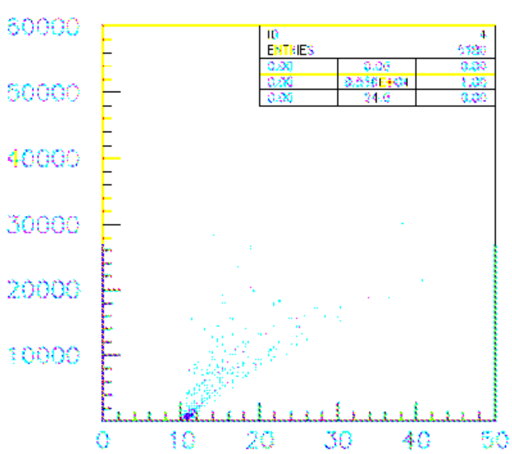
Smeared Source, Attenuation Length and Surface Roughness included, Glue around the fiber

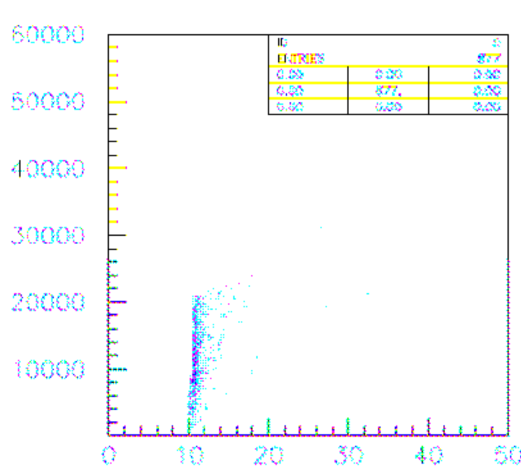


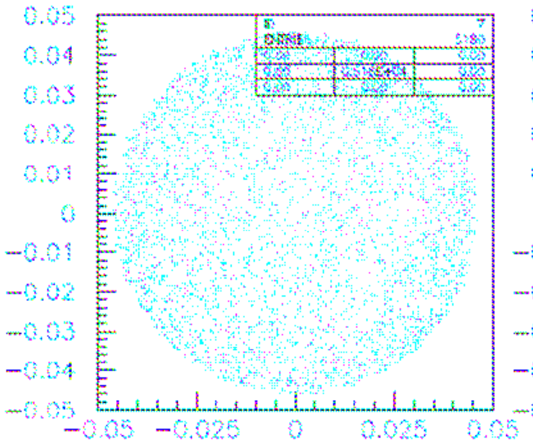
Upstream Tof Seq.1



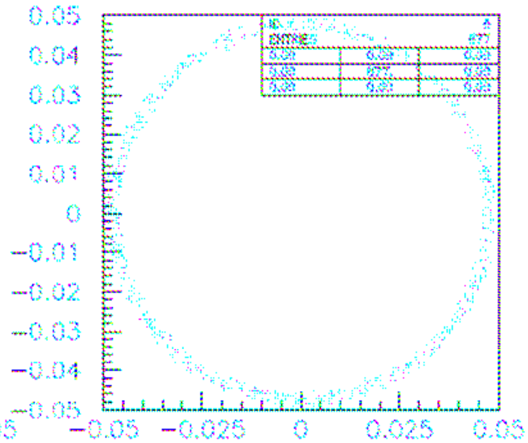
Upstream Tof Seq.2



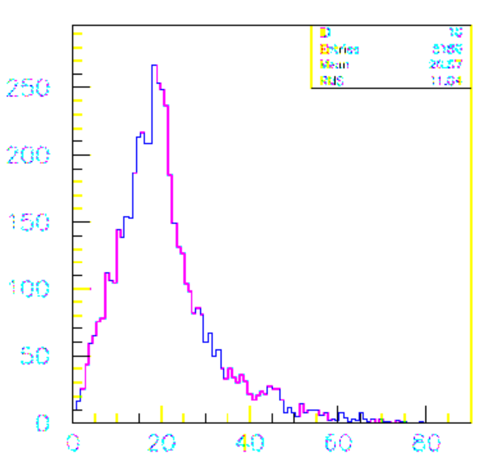




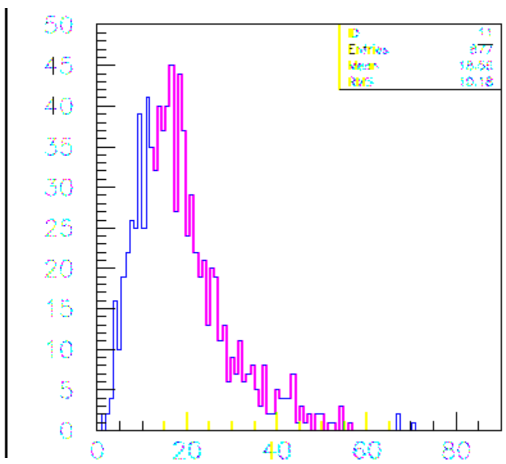
Upstream x and y position Seq.1



Upstream x and y position Seq.2



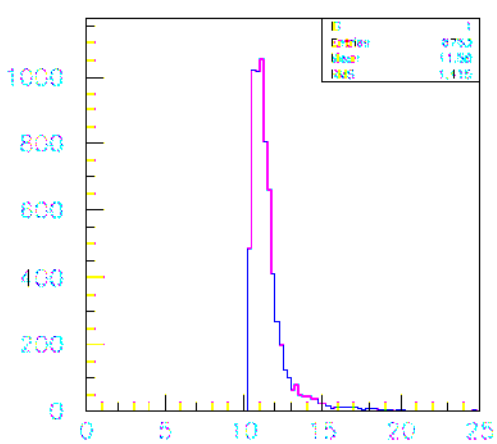
Upstream exit theta Seq.1

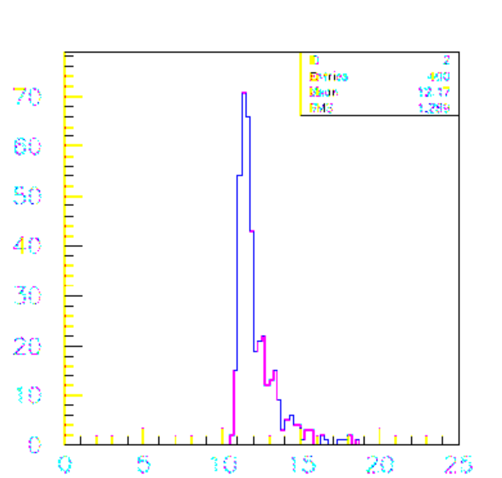


Upstream exit theta Seq.2

Appendix III

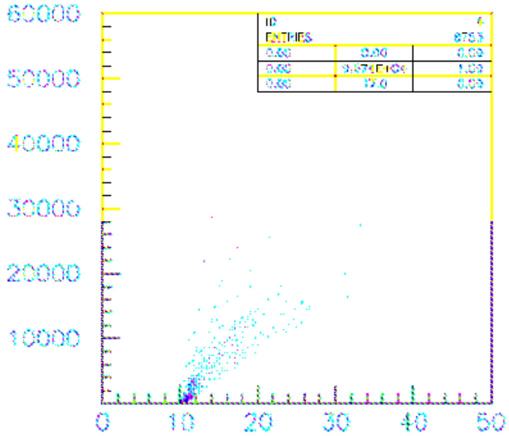
IORs as in Part 2, Smeared Source, Attenuation Length and Surface Roughness included, Glue around the fiber

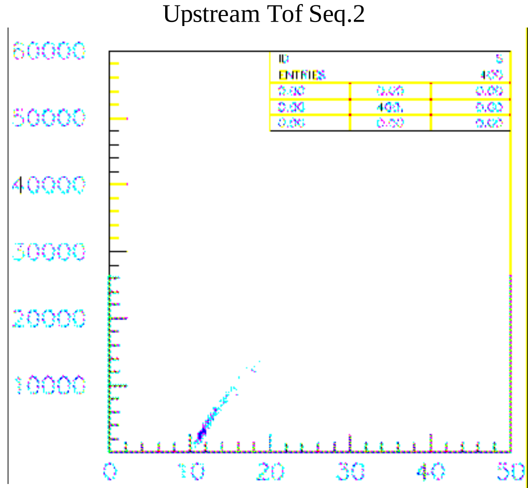




Upstream Tof Seq.1

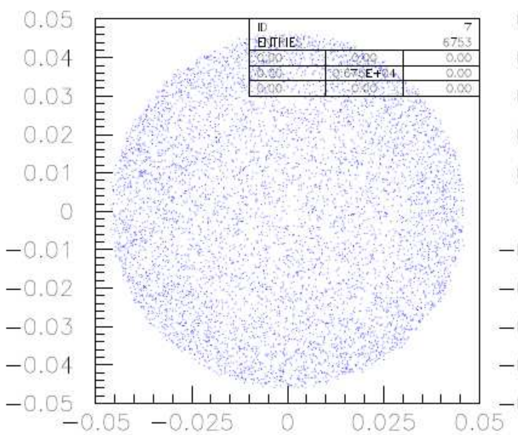
Upstream Tof Seq.2

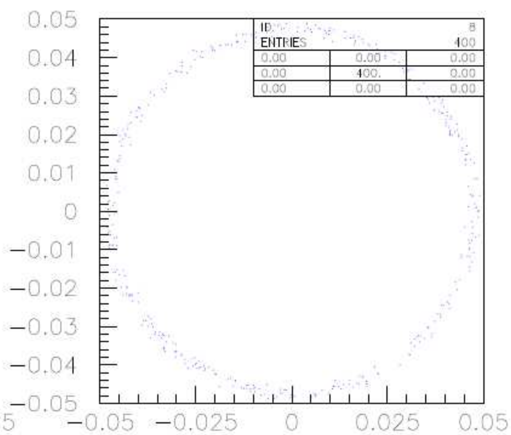




Upstream bounces vs Tof Seq.1

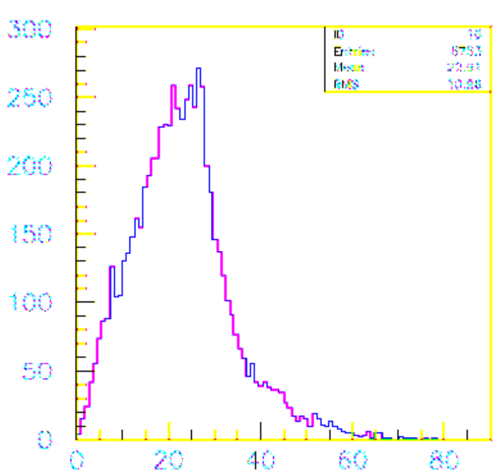
Upstream bounces vs Tof Seq.2

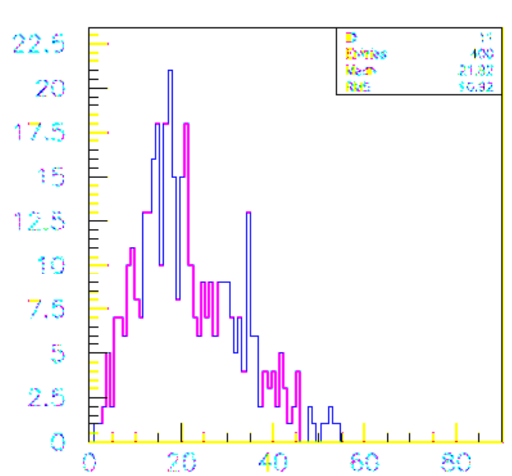




Upstream x and y position Seq.1

Upstream x and y position Seq.2





Upstream exit theta Seq.1

Upstream exit theta Seq.2