Instituto Nacional de Astrofísica, Optica y Electrónica.

Reporte Técnico

STUDY ON MICROMIRRORS

Eugénie Dalimier
Guillaume Lecamp
Francisco-J Renero-C

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El reporte que tiene en sus manos ó en su computadora, es el resultado del entrenamiento (prácticas profesionales) de Eugénie Dalimier y Guillaume Lecamp, asesorados por un servidor. Ambos estudiantes de la Ecole Supérieure d'Optique (SupOptique) en Francia.

Este reporte es ahora parte fundamental para interesados en al caracterización de micro-componentes ópticos fabricados en silicio, que decidí ponerlo a disposición del publico en la Biblioteca del Instituto.

El reporte se encuentra en la forma original escrita por Dalimier y Lecamp.

Atte.

Francisco Renero
INAOE
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Sta. Tonantzintla, Puebla a 12 de diciembre de 2007.

Study on micromirrors

By Eugénie Dalimier
and Guillaume Lecamp

Directed by Francisco Renero August 2002

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E. Dalimier
G. Lecamp

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General introduction

The aim of this project is to study micromirrors, this is to say their characteristics as well as their possible utilization. These micromirrors have been made using the silicon etching method with KOH:H_2O (cf Optical Engineering/November 1994/Vol.33 No.11). A picture of one of this micromirror, seen through an optical microscope, can be found in Appendix 1.

The first chapters will present the characterisation of about 75 such micromirrors, classified in five different sizes (the sketches are given in Appendix 2). Different methods have been used to measure optical parameters, such as the diameter, the circularity, and the focal length, of the micromirrors. The consistence of the results will be studied, amongst each kind of samples as well as amongst the methods.

In the last chapter, we will focus on the utilization of these micromirrors, especially for a "4f" system very used in telecommunications, and for a imagery "ended-ended" system.

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Introduction

This chapter presents the first series of measurements in order to characterise the micromirrors, made in the "cuarto limpio" with the perfilometer and the optical microscope. We will check whether the results are consistent or not.

The first section will describe the method used to obtain the sagitta with a perfilometer. The second part will study the diameter with a microscope. Finally, the focal length will be calculated from these two parameters.

I Measurements of the sagitta of micromirrors

This section will study the sagitta of the etched mirrors through a method of measurement described in the first part. Then we will analyse the precision and the validity of this method and finally gather the results that have been obtained.

1-Method of measurement with a perfilometer

a) Principle

First a brief definition of the sagitta. The sagitta **as shown on the figure 1**, is the distance from the base of the mirror to the top of the edges.

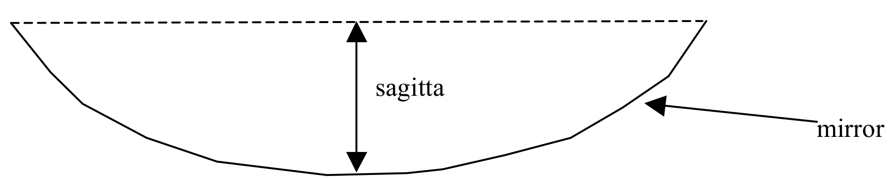

Figure1: Sketch of sagitta in an spherical mirror.

The principle of the measurement is simple. **We draw the profile of each micromirror as near as possible from the base** and then we obtain the sagitta through an easy difference between the height of the base and the edges. A very precise measurement is necessary (the sagitta of the samples are about 10 micrometers) which is difficult to obtain. Trying to reach this aim, the measurements is conducted with a perfilometer.

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b) The perfilometer

As stated before, the perfilometer is an instrument that draws the profile of the sample. It is a **mechanical instrument**, which uses a simple pin moving over the surface that we study (cf figure 2)

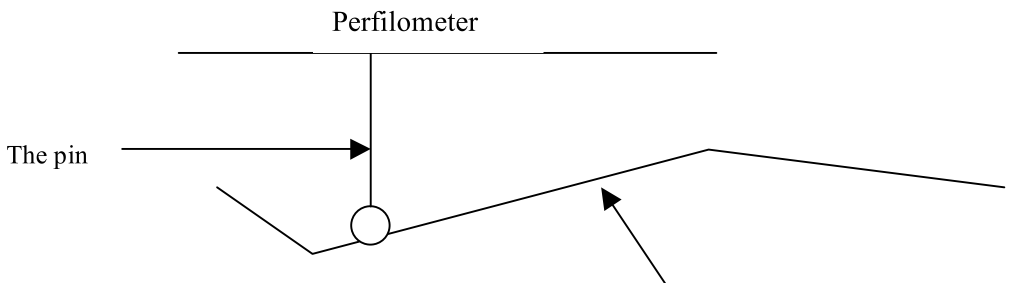

Fig.2: Perfilometer sketch.

Then the variations are displayed on a figure as the one below.

Finally with a data processing analysis done by the perfilometer itself, the perfilometer gives us the depth of the depression and the distance between the two cursors, seen on the figure above.

2-Precision

As we want to compare the different samples, it is very important to know if the measurements are accurate or not. So we have to study carefully all the precision problems.

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Here there are three causes of uncertainty: the size of the pin that do the measures, the precision of the perfilometer itself (depending on the scale we use) and the imprecision due to the operator who makes the experiment.

a) The placement of the pin

The pin that does the measurements has a spherical tip (with a radius of 6 micrometers). So, when placing the pin near a diameter of the circle (cf figure 3) it cannot be placed right on it but with a precision of about 2 micrometers.

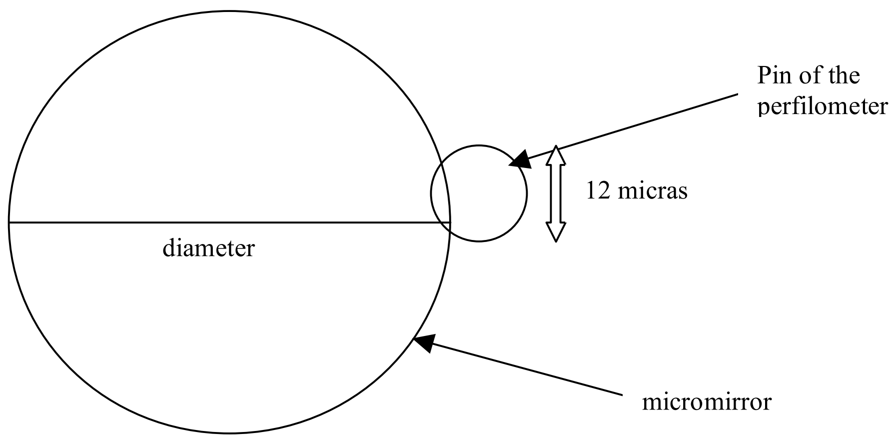

Fig.3: Diagram of the pin of the perfilometer and the micromirror.

This imprecision in the exact position of the diameter implies that we are not measuring the sagitta but a smaller depth. From figure 4, we estimate this imprecision to $\Delta s = s - s' = \frac{\delta \times s}{R}$ (cf graphic and basic geometrical operations)

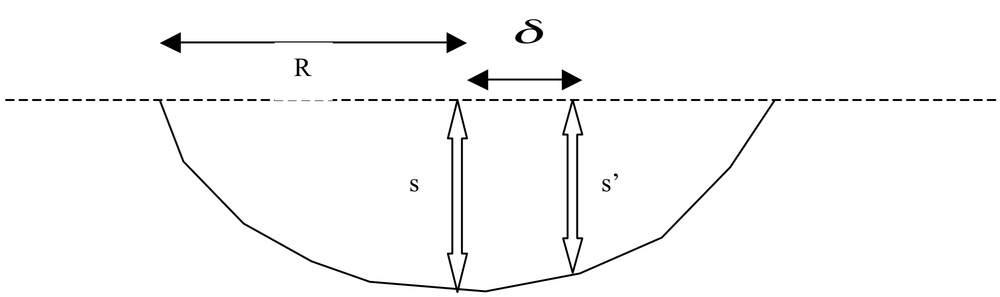

Fig.4: Parameters to calculate the measurement imprecision due to the size of the end of the pin.

For the pattern issues from $d_0 = 10\mu m$, where d_0 is the diameter of the hole at the beginning of the etching process, we determine that $\boxed{\Delta s = \frac{2}{150} \approx 1.3\%}$.
This imprecision would get smaller if the diameter increases so here we estimate the worst one. This imprecision is also impossible to reduce but is included in the imprecision due to the manipulator, which we talked about later, so that we don't care much of it.

b) The precision of the perfilometer

The perfilometer can be used with two scales: one for the holes shallower than 160µm and another one for deeper holes.
We use the first scale for the holes $d_0 = 10\mu m, 20\mu m, 30\mu m$. The sagitta precision is 0.5nm (cf manual of the perfilometer), which is completely negligible compared to the imprecision due to the pin ($\Delta s = 1.3\%$).
For the hole $d_0 = 40\mu m, 50\mu m$ we use the other scale which leads to a precision of 5nm, negligible too. **Finally we conclude that the perfilometer precision is not a limitation for our measurements.**

c) Repeatability

To test the uncertainty due to the operator, we took many measurements on the same micromirror and then calculated the standard deviation.
Test on the sample A110 in two perpendicular directions, gave the results shown in the table below.

Table1

Sample	sagitta 1 (microns)	sagitta 2 (microns)	sagitta 3 (microns)	sagitta 4 (microns)
A110	4.39	4.35	4.33	4.38
A110 a 90°	4.29	4.32	4.29	4.37

Average (microns)	**4.34**
Stand dev (microns)	**0.03**

We obtain a standard deviation of 0.8% that is good, and small enough to study and compare the sagitta of the samples. This result is smaller than the imprecision due the positioning of the pin (cf I.2.1)), we have probably overestimated it. These results indicate that our measurements on the different samples should be repeatable, this is the aim of the following section.

3-Results

We have made as many measurements as possible but sometimes the quality of the micromirrors was poor or the sample was too small so that the pin dragged the sample. Then we gather the results of d_0 and calculate the average and the standard deviation (the results are given in Appendix 3).

$$d_0 = 10\mu m, \ sagitta_{10} = 4.4 \pm 2.3\%$$

Table 2

Sample	Sagitta (microns)
A110	4.392
A310	4.403
A410	4.215
B110	4.328
B210	4.472
B410	4.380
B610	4.487
D710	4.553
D810	4.144
D910	4.145
E410	4.499
Average (microns)	**4.4**
Stand dev (microns)	**0.1**

$$d_0 = 20\mu m, \ sagitta_{20} = 9.0 \pm 2.2\%$$

Table 3

Sample	Sagitta (microns)
A120	8.762
A320	8.752
A420	8.941
B120	9.209
B220	9.182
B420	8.965
B520	8.993
B620	9.137
C220	8.855
D820	8.721
D920	8.971
D1020	8.660
E220	9.134

E320	9.538
E420	8.809
Average (microns)	**9.0**
Stand dev (microns)	**0.2**

$d_0 = 30\mu m$, $sagitta_{30} = 13.2 \pm 1.5\%$

Table 4

Sample	**Sagitta (microns)**
A130	13.01
A330	13.59
B130	13.67
B230	13.20
B430	13.10
B530	13.45
B630	13.13
C230	13.07
D930	13.27
D1030	12.93
E230	13.38
E330	13.00
E430	13.40
Average (microns)	**13.2**
Stand dev (microns)	**0.2**

$d_0 = 40\mu m$, $sagitta_{40} = 17.4 \pm 2.3\%$

Table 5

Sample	**Sagitta (microns)**
A140	16.85
A240	16.83
A340	17.40
A440	17.61
A540	17.10
B140	17.63
B240	17.47
B440	17.68
B540	17.17

C240	17.26
D940	17.94
D1040	16.42
F140	17.96
Average (microns)	**17.3**
Stand dev (microns)	**0.4**

$d_0 = 50\mu m$, $sagitta_{50} = 21.0 \pm 1.9\%$

Table 6

Sample	**Sagitta** (microns)
A150	21.45
A250	20.41
A350	21.99
A450	21.56
A550	21.46
B450	20.99
C350	20.99
D350	20.83
D950	21.63
D1050	20.45
Average (microns)	**21.2**
Stand dev (microns)	**0.4**

The important thing to keep in mind after all these measurements is that as **the worst standard deviation is 2.3% which can be considered as acceptable**.

After a long series of measurements of sagitta on many samples, we can conclude that the fabrication process of micromirrors is consistent with respect of the properties of micro-mirrors (standard deviation smaller than 3%). This conclusion means that we are now able to built **regular array of micromirrors** and also **predict precisely the sagitta and the focal length**.

II Measurement of the diameter

1-Precision of the measurement

To measure the diameter of the etched mirrors, we chose to work with the optical microscope. Indeed, we realised that we obtain a higher precision with this instrument than with the perfilometer.

a) Precision on the microscope

For the microscope, used with the yellow objective, each graduation corresponds to 5 μm. We must not forget to count this imprecision twice (once for each edge of the etched mirror). Therefore, the uncertainty for each measure is evaluated at **10 μm**, and this will remain the same for all the diameters.

Table 7

Pinhole size (μm)	Uncertainty (%)
10	**3.3**
20	**2.4**
30	**2**
40	**1.9**
50	**1.8**

NB: these uncertainties were calculated from the diameters; as we obtained two different values (as is seen later), we chose the average of the two to calculate the uncertainty in percentage.

b) Precision on the perfilometer

For the perfilometer, we include two different uncertainties *a* and *b*.

Firstly, we measure the diameter with a pin, whose thickness, unlike the one of the graduations of the microscope, must not be overlooked. In fact, the thickness of this pin is evaluated at 12 μm, whereas the graduations on the microscope are no more than 1μm. This thickness has an important role, since it prevents us from pointing and measuring the direction of the exact diameter, as shown below.

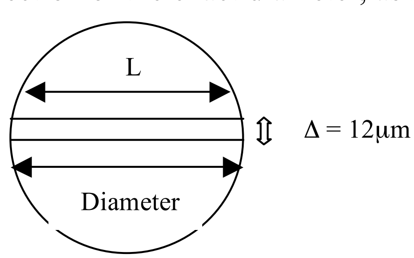

Figure 5. Thickness fo the pin from the diameter.

Referring to the figure, we can get this equation

$$L = \sqrt{D^2 - 2D\Delta - 4\Delta^2}$$

Hence, the uncertainty *a* coming from it is

$$a = \frac{D - L}{D} = \frac{D - \sqrt{D^2 - 2D\Delta - 4\Delta^2}}{D}$$

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We have calculated this uncertainty for the different diameters that we have measured. The results are shown in Table 8 below.

Table 8

Pinhole size (μm)	Uncertainty (%)
10	**4.2**
20	**4**
30	**3.5**
40	**3.3**
50	**3.1**

The second uncertainty comes from the perfilometer itself. While reading the figures on the screen of the perfilometer, we note that the precision is 5 μm for the 40 and 50 μm-large pinholes, and 2 μm for the others (depending on the calibration as discussed in section I.2)b)). We must not forget to count it twice (once for each edge of the etched mirror). The Table 9, eventually, is obtained adding the two uncertainties.

Table 9

Pinhole size (μm)	Uncertainty (%)
10	**5.5**
20	**5**
30	**5.5**
40	**5.2**
50	**4.9**

Comparing the Tables 7 and 9, it is evident that we have a better precision, for the diameter measurement, with the microscope than with the perfilometer.

2-Results

We did a series of measurements on the different sizes of pinholes. For each sample, we determined the diameter after alignment with the direction of the crystal (diameter 1), and then along the diagonal (diameter 2). Each measurement was made twice, in one direction and then perpendicular to it.

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First measurement (diameter 1) Second measurement (diameter 2)

Figure 6. Two measurements of the diameter to study the circularity.

As it was done for the sagitta, the results are given for each size of pinhole in the Tables 10 to 14.

We must remember that the precision on the measurements is of 10 micrometers, except for a few ones for which the uncertainty doubles (these measurements are coloured in the tables). One can also note that a few measurements are missing, since the samples were damaged.

The parameter p of circularity can also be calculated for each sample. As shown in the article (1), it is defined as

$$p = \frac{d_1 - d_2}{d_2}$$

where d_1 and d_2 are the two diameters coming from the two measurements (d_2 is the biggest one). This parameter appears in percentage in the tables.

Table 10. Hole of 10 μm

Sample	diameter 1 (μm)	Diameter 2 (μm)	Circularity (%)
A110	305	310	1.61
A310	305	310	1.61
A410	305	305	0.00
B110	295	300	1.67
B210	305	310	1.61
B410	305	310	1.61
B510	300		
B610	305	310	1.61
C210	300	305	1.64
C310	305	310	1.61
D710	310	315	1.59
D810	295	300	1.67
D910	295	300	1.67
E210	305	310	1.61
E410	310	315	1.59
F310	300	305	1.64
Average	**303**	**308**	**1.6**
Standard dev	**4**	**4**	**0.2**

We can note that the standard deviation is smaller than the uncertainty calculated before: **5 µm instead of 10 µm** (which represents 3.3% of the diameter). This may be explained by the fact that the uncertainty was overestimated. In fact, we may have a better precision than two graduations. Nevertheless, we will keep the largest imprecision, and we will do the same later. Thus we have

$$\mathbf{D_1 = (300 \pm 10)\ \mu m,\ \ and\ \ \ D_2 = (310 \pm 10)\ \mu m}$$

It appears here that the imprecision on the measurements is larger than the parameter of circularity : 3.3% in front of 1.6%. Therefore, it would not have sense to retain his value, and we can consider this series of sample as circular.

Table 11. Hole of 20 µm

Sample	Diameter 1 (µm)	Diameter 2 (µm)	Circularity (%)
A120	415	430	3.49
A320	415	425	2.35
A420	415	430	3.49
B120	415	435	4.60
B220	420	440	4.55
B420	420	435	3.45
B520	415	430	3.49
B620	415	430	3.49
D820	410	430	4.65
D920	420	435	3.45
D1020	405	420	3.57
E220	420	430	2.33
E420	415	430	3.49
F220	405	420	3.57
Average	**415**	**430**	**3.6**
Stand dev	**3**	**4**	**0.4**

This series of measurement is similar to the first: better standard deviation than the uncertainty, and circularity parameter just a bit larger than this uncertainty (2.4 %). It is thus difficult to discuss the circularity for this case. We will only keep

$$\mathbf{D_1 = (410 \pm 10)\ \mu m,\ \ and\ \ \ D_2 = (430 \pm 10)\ \mu m.}$$

Table 12. Hole of 30 µm

Sample	Diameter 1 (µm)	Diameter 2 (µm)	Circularity (%)
A130	480	510	5.88
A330	490	520	5.77

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A430	490	530	7.55
B130	485	515	5.83
B230	480	510	5.88
B430	485	515	5.83
B530	490	515	4.85
B630	480	510	5.88
C230	470	495	5.05
D930	485	515	5.83
D1030	470	500	6.00
E230	485	515	5.83
E330	485	510	4.90
E430	485	510	4.90
average	**483**	**512**	**5.7**
Stand dev	**5**	**6**	**0.4**

We have

$$\mathbf{D_1 = (480 \pm 10)\ \mu m,\ \ and\ \ \ D_2 = (510 \pm 10)\ \mu m.}$$

At this point, the uncertainty (we still keep the biggest: 1.6% here) is far smaller than the parameter of circularity. Therefore, we can note this value: **5.7%.**

Table 13. Hole of 40μm

Sample	Diameter 1 (μm)	Diameter 2 (μm)	Circularity (%)
A140	500	560	10.71
A240	500	565	11.50
A340	500	570	12.28
A440	500	580	13.79
A540	505	575	12.17
B140	500	580	13.79
B240	500	575	13.04
B340	505		
B440	505	580	12.93
B540	500	565	11.50
C140	490	570	14.04
C240	490	565	13.27
D840	495	585	15.38
D940	500	575	13.04
D1040	495	565	12.39
F140	495	575	13.91
F240	495	570	13.16
average	**499**	**572**	**12.9**
Stand dev	**4**	**6**	**0.9**

In this table, we can note some values in grey: the uncertainty is 20 micrometers, unlike the others. However, we can see that the standard deviation does not reflect this loss of precision. Again, we keep the uncertainty of two graduations as calculated before.

Thus,

$$\mathbf{D_1 = (500 \pm 10)\ \mu m, \ and \quad D_2 = (570 \pm 10)\ \mu m.}$$

The parameter of circularity has risen as it was predicted in the article (1): **12.9%.**

Table 14. Hole of 50μm

Sample	diameter 1 (μm)	Diameter 2 (μm)	Circularity (%)
A150	510	625	18.4
A250	515	610	15.6
A350	510	615	17.1
A450	510	625	18.4
A550	515	630	18.3
B150	505	610	17.2
B350	510	610	16.4
B450	510	615	17.1
C150	500	610	18.0
C250	495	615	19.5
C350	500	605	17.4
D350	505	640	21.1
D950	515	635	18.9
D1050	510	615	17.1
F350	505	615	17.9
average	**508**	**620**	**18**
Stand dev	**5**	**8**	**1**

We note

$$D_1 = (510 \pm 10)\ \mu m, \ and \quad D_2 = (620 \pm 10)\ \mu m.$$

This final table enhances the higher standard deviation probably caused by the important number of values of larger uncertainty than usual. However, this standard deviation remains less important than the uncertainty of two graduations. We can definitely *assume that the calculation was overestimated, and that* ***the standard deviation is always very good: for all the measures, it goes from 0.7 % to 1.3 %.***

The high parameter of circularity, 18 %, reflects the squarish pattern we could observe on these not entirely formed etched mirrors.

We would have wanted to compare the parameters of circularity we have measured, to those given in the article (1) for different etching depths, but we do not think this is possible, for the conditions are completely different. Moreover, the empirical equation giving the depth *h,* using the values of *D* the diameter calculated and of d_0 the diameter of the initial opening in the article (1):

$$\frac{D}{d_0} = 7.8 * \left(\frac{h}{d_0}\right)^{0.58}$$

must not be relevant here.

Nevertheless, our results are consistent, as they indicate a rise of the diameters parallel to a rise of the parameter of circularity.

III Calculation of the focal length

As seen in the article (1), the focal length is given by the equation

$$f = \frac{D^2}{16s}$$

For this calculation, we use the measures of the sagitta given by the perfilometer, and those of the diameters given by the microscope. Amongst the two diameters, we use the smallest value, as it represents best the circularity of the pattern. However, as the two values of diameter sensibly differ, this choice is arbitrary, and will be discussed again in Chapters C and D.

Again, a table was done for each kind of pinhole size.

Table 15. Hole of 10µm

Sample	Sagitta (µm)	Diameter (µm)	Focal length (µm)
A110	4.392	305	1324
A310	4.403	305	1320
A410	4.215	305	1379
B110	4.328	295	1257
B210	4.472	305	1300
B410	4.380	305	1327
B610	4.487	305	1296
D710	4.553	310	1319

D810	4.144	295	1313
D910	4.145	295	1312
E410	4.499	310	1335
average	4.4	300	**1320**
Stand dev	0.1	10	**20**

We have **f = 1320 μm ± 1.5%**

Table 16. Hole of 20μm

Sample	Sagitta (μm)	Diameter (μm)	Focal length (μm)
A120	8.762	415	1228
A320	8.752	415	1230
A420	8.941	415	1204
B120	9.209	415	1169
B220	9.182	420	1201
B420	8.965	420	1230
B520	8.993	415	1197
B620	9.137	415	1178
D820	8.721	410	1205
D920	8.971	420	1229
D1020	8.660	405	1184
E220	9.134	420	1207
E420	8.809	415	1222
average	8.9	410	**1210**
stand dev	0.2	10	**20**

We note **f = 1210 μm ± 1.7%**

Table 17. Hole of 30μm.

Sample	Sagitta (μm)	Diameter (μm)	focal length (μm)
A130	13.01	480	1107
A330	13.59	490	1104
B130	13.67	485	1075

B230	13.20	480	1091
B430	13.10	485	1122
B530	13.45	490	1116
B630	13.13	480	1097
C230	13.07	470	1056
D930	13.27	485	1108
D1030	12.93	470	1068
E230	13.38	485	1099
E330	13.00	485	1131
E430	13.40	485	1097
average	13.2	480	**1100**
Stand dev	0.2	10	**20**

The result is **f = 1100 µm ± 1.8%**

Table 18. Hole of 40µm

Sample	Sagitta (µm)	Diameter (µm)	Focal length (µm)
A140	16.85	500	927
A240	16.83	500	928
A340	17.40	500	898
A440	17.61	500	887
A540	17.10	505	932
B140	17.63	500	886
B240	17.47	500	894
B440	17.68	505	902
B540	17.17	500	910
C240	17.26	490	869
D940	17.94	500	871
D1040	16.42	495	933
F140	17.96	495	853
average	17.3	500	**900**
Stand dev	0.4	10	**20**

Here we have **f = 900 µm ± 2.2%**

Table 19. Hole of 50µm

Sample	Sagitta (µm)	Diameter (µm)	Focal length (µm)
A150	21.45	510	758

A250	20.41	515	812
A350	21.99	510	739
A450	21.56	510	754
A550	21.46	515	772
B450	20.99	510	774
C350	20.99	500	744
D350	20.83	505	765
D950	21.63	515	766
D1050	20.45	510	795
average	21.2	510	**770**
Stand dev	0.4	10	**20**

Finally, for the largest mirror, **f = 770 µm ± 2.6%**

For all the focal lengths, the standard deviation appears to be quite good (from 1.5% to 2.6%). We can compare it to the theoretical uncertainty calculated with the uncertainties on *D* and *s* from the definition of *f*:

$$\frac{\Delta f}{f} = 2\frac{\Delta D}{D} + \frac{\Delta s}{s}.$$

We find with this formula values that are 3 to 6 times bigger to the standard deviations.

Conclusion

To conclude, we can say that the measurements are very repeatable: the standard deviation for a same original hole is at most 1.3% for the diameter, and 2.6% for the focal length. As for the focal length, though, we made a restriction in using only one value of the diameter. Thus the problem has to be studied more carefully later.

Although both the perfilometer and the optical microscope are simple methods, for their functioning as well as for their utilisation, they seem to give reliable results. However it is necessary to check them with other methods, as it will be done in Chapters B, C and D. This will be the occasion to rethink the problem of the focal length.

E. Dalimier
G. Lecamp

Introduction

In order to confirm our results obtained in the "cuarto limpio", the same samples of micromirrors were studied with the interferometric microscope. This microscope only enables us to measure the sagitta, and that is what we used it for.

We will first present the interferometric microscope and its precision, before showing the results obtained with it.

I Presentation of the interferometric microscope

1-Functioning of the interferometric microscope

This device, as it appears in its name, can be used as an interferometer as well as a microscope.

Indeed, as shown on the Appendix 4, it is formed as a Twymann-Green interferometer: the incident illumination is divided at a glass beam-splitting cube into reference and sample arms, and reflected by the mirrors. For a common Twymann-Green interferometer, these two mirrors can be translated and tilted as so to obtain interference between the two waves, and deduct the shape of the sample from the fringes seen. Here, we can only translate them, and by rotating the tilt plates, the beams themselves are tilted.

Moreover, objectives are inserted before the mirrors to focus the parallel beams on the surfaces. Therefore, only a small surface (the size of the focal point) is compared to the reference plane and we can actually visualise the sample.

Finally, we can note on the figure that different sources can be used, depending on what is wanted.

2-Utilisation of the interferometric microscope

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a) Adjustment of the microscope

We chose here to work with the mercury lamp, placed before a filter, which select the wavelength (550 nm).

The first thing to do is to adjust the optical part of the microscope. In fact, both the reference mirror and the sample must be translated in order to be in the focal plane of the objectives. This is done one mirror at a time, while letting the incident illumination pass only in one of the arm. Each time, the aperture stop is reduced to visualise the focal plane.

One can note that for our experiment, we used the objective ×100, which was the more accurate objective amongst the ones available. However, this objective was slightly too strong, and whereas the 10 microns micromirrors would perfectly fit in the ocular stop (cf Appendix 5), the 40 and 50 microns mirrors appeared too big to be studied, as is seen below.

b) *Adjustment of the interferometer*

After the microscope part of the system device has been adjusted, we can focus on the interferometric part. Indeed, as it was said before, the aim of this experiment is to measure the sagitta, using interferometric data. With this optical system, when the two mirrors are parallel, such a figure is obtained as given in Appendix 5, where the rings enhance the curvature of the mirror.

Counting the number of fringes from the centre to the edge gives us the height, this is to say the sagitta, of the micromirror, with the formula

$$s = N\frac{\lambda}{2}$$

where s is the sagitta, N the number of fringes and λ the wavelength.

As this measurement is given in wavelength, it is important to know exactly the wavelength we are working with, and so is done.

This method of measurement prevents us from studying the 40 and 50 microns. Indeed, it is necessary for the measurement to see with the ocular at least half of the diameter, in order to count the fringes from the centre to the border. This was only obtained with the 10, 20, and 30 microns pinholes (see Appendix 5 and 6).

In practice, the tilt plates are rotated in order to obtain the sample and the reference mirror parallel: we then do not observe any parallel fringes between the micromirrors. The only visible fringes are the rings pointing the curvature of the mirrors.

E. Dalimier
G. Lecamp

c) Precision of the measurement

As each fringe correspond to λ/2 and as the black fringes can definitely be distinguished from the white ones, we have a precision of λ/4 both at the beginning and at the end of the counting. Eventually, **the precision on the measurement is λ/2 which represents 0.28 microns**.

II Results

1-Numerical results

For each sample studied in the "cuartio limpio", we measured the number of fringes from the centre to the border, and calculated the sagitta with the equation given in I.2-b)

As it was said before, with the objective used (*100), we could not study the samples coming from pinholes of 40 and 50 microns.

Moreover, we had some difficulties to take pictures of the image seen in the ocular, since the contrast or the luminosity was not always good enough. It is possible to adjust these parameters by enlarging or shrinking the field pupil: the more luminosity we get, the less contrast we have. However for some reasons we can not explain, we could not obtain the good balance between these parameters for a few samples, which made these samples unusable.

Thus the following tables gather the measurements of most micromirrors coming from 10, 20, and 30 microns pinhole sizes.

$$d_0 = 10\mu m \quad ; \quad sagitta_{10} = 4.4\mu m \pm 6.3\%$$

Table 1

Sample	nbr of fringes	sagitta (μm)
A110	16	4.44
A310	16	4.44
A410	15.5	4.30
B110	16	4.44
B210	17	4.72
B410	16.5	4.58
B510	15	4.16

B610	16	4.44
C210	16	4.44
C310	15.5	4.30
D810	15	4.16
D910	14.5	4.02
D1010	16	4.44
E410	16.5	4.58

Average	**15.8**	**4.39**
stand dev	**0.5**	**0.14**
Uncertainty	**1**	**0.28**

$d_0 = 20\mu m$, $sagitta_{20} = 8.9\mu m \pm 3.1\%$

Table 2

Sample	nbr of fringes	sagitta (μm)
A120	31	8.60
A320	31.5	8.74
B120	33.5	9.30
B220	32.5	9.02
B420	33	9.16
B520	32	8.88
B620	32.5	9.02
C220	32	8.88
C320	31.5	8.74
D820	31	8.60
D920	32	8.88
E220	33	9.16
E420	32	8.88

Average	**32.1**	**8.91**
stand dev	**0.6**	**0.17**
Uncertainty	**1**	**0.28**

$d_0 = 30\mu m$, $sagitta_{30} = 13.2\mu m \pm 2.1\%$

Table 3

Sample	nbr of fringes	sagitta (μm)
A130	48	13.32
A430	51	14.15
B130	49	13.60
B230	47	13.04
B430	47	13.04
B530	48	13.32

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B630	47.5	13.18
C230	46.5	12.90
D930	47.5	13.18
D1030	46	12.77
E230	47.5	13.18
E430	46.5	12.90

average	**47.6**	**13.22**
stand dev	**0.9**	**0.25**
uncertainty	**1**	**0.28**

2-Analysis of the results

In all the tables of results (Tables 1 to 3) appeared both the standard deviation and the uncertainty as defined above (in part I.2-c)). For the final result, the largest of those two was kept and expressed in percentage.

The standard deviations (from 1.9% to 3.2%) always remain below the uncertainty of each measurement (from 2.1% to 6.4%), and that highlights the very good repeatability of the samples.

We can point out that the results for these three kinds of micromirrors are exactly the same as the ones obtained with the perfilometer, with our precision. This point can definitely be enjoyed!

Conclusion

For the reasons given above, we can definitely be satisfied with the results obtained with the interferometric microscope.

It was pointed out that the same results were found for both the interferometric microscope and the perfilometer. Nevertheless, if we compare the uncertainties (apart from the standard deviation), it appears larger here than for the perfilometer. As for the standard deviation, it remains quite the same for both methods. Therefore, as the interferometric microscope requires more time for the adjustments and the data taking, the perfilometer method seems preferable.

E. Dalimier
G. Lecamp

Introduction

The aim of this new study of the focal length of the micromirrors **is to confirm the first results** obtained with the perfilometer and the optical microscope. These new measurements are taken with a very simple optical device, the spherometer. The first section explains the operation of it, and the second section gathered the results and their analysis.

I Presentation of the spherometer

1-Operation of the spherometer

This device has a really simple functioning, it is composed of an objective, a beam-splitter, a reticule, an ocular and a light source (cf. figure 1).

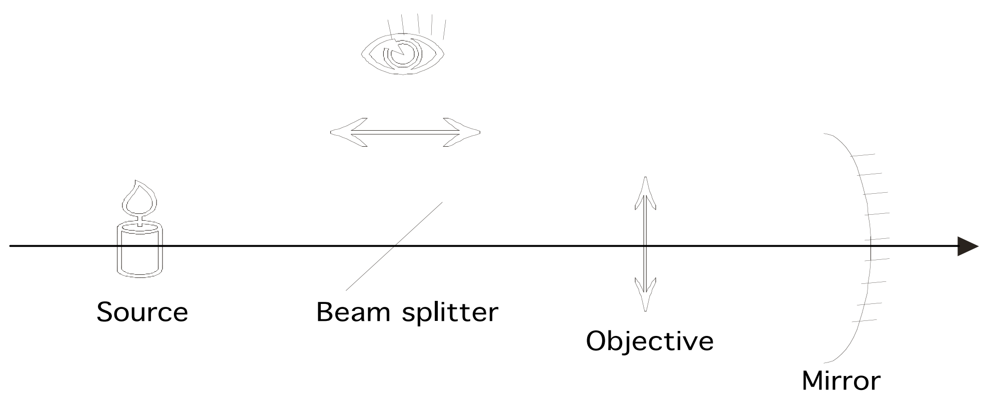

Figure 1: Sketch of a spherometer

The aim of these measurements is to obtain the focal length and this instrument permit to determine the position of the base and of the centre of curvature of the mirror. In fact when we point one of these positions the beam, come back through the same path, so that we can observe the reticule. Then **pointing the base of the mirror and the centre of curvature permitted to calculate** C, the radius of curvature and additionally **f, the focal length** since $f = \frac{C}{2}$.

2-Interest of this new method

This method is very used to calculate the focal length of large mirrors (diameter over 10 mm) because **it is a very simple** one that need very few devices and it also **gives directly the focal length without calculations**. Nevertheless many problems occur due to the size of the mirrors (diameter of about 300 m): first the alignment must be very sharp, then the light source have to be very bright for the reflective light is very weak and finally the reticule should be large to be sure that a part of it reaches the micromirror.

When these problems are gone over and especially the one concerning the alignment, we are able to determine the focal length of each sample. But before giving these results to know if they are accurate, we have to study the precision of the spherometer.

3-Precision

Three different phenomena can cause uncertainty in the measurement of the focal length: the misalignment, the pointing of the base and the centre of curvature of the mirror and the operator himself.

a) The misalignment

If all the different devices of the measurement system are not aligned, we will not measure the distance F, between the centre of curvature and the base of the mirror but another uninteresting length called D (cf. figure 2).

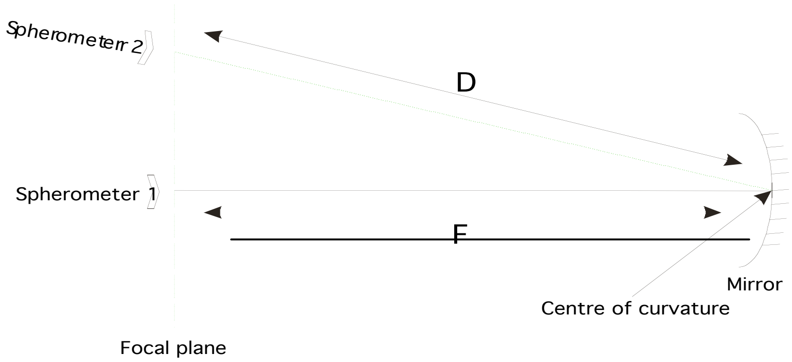

Figure 2: Misalignment problem

Here, the small size of the mirror is an advantage. In fact the mirror is so small that a very little misalignment lead to the fact that the beam will not reflect on its surface so that we will not observe the reticule when we try to observe the base of the mirror.

Finally we consider that **there is no misalignment** but **the adjustments are very accurate and therefore difficult to do**.

b) The pointing

This problem is a classic uncertainty when using the spherometer. Actually every optical system is victim of aberrations, so that there is always **a zone of focalisation but not a perfect point**. Moreover our micromirrors are not perfectly circular so that this zone is much larger than usually.

We estimate this uncertainty on the two pointings: the uncertainty on the centre of curvature is estimated to ±40 µm and the one on the base is estimated to ±10 µm, finally we have **an uncertainty of ±50 µm**, just on the pointings.

c) Repeatability

To test the uncertainty due to the operator we took many measurements on the same micromirrors and calculated the standard deviation.
Test on the sample B210 gave the results shown on the table 1.

Table1

measurement	focal length (mm)
eugenie 1	2.72
eugenie 2	2.72
eugenie 3	2.68
eugenie 4	2.70
eugenie 5	2.73
guillaume1	2.71
guillaume 2	2.70
guillaume3	2.71
guillaume4	2.69
guillaume5	2.71

Average	**2.70**
Stand. dev.	**0.02**

The standard deviation is about 0.7% which is very small but we do not forget that the uncertainty is more important (±50 µm that means 3.7%) and that the operator can point exactly the same place (that means a standard deviation of 0%), even if this point is completely wrong.

In conclusion **the whole uncertainty is about 4%** and it is due to the large area of focalisation but not to the operator.

E. Dalimier
G. Lecamp

II Results

1-The aim of the measurements

The measurement are taken on the sample B2## because it has all the different holes and also because these holes are good one.
We make measurements only on this sample since the aim of this experiment is just to check the coherence of the former measurements taken with the perfilometer.

2-Numerical results

This section contained the numerical results (table 2) given with their uncertainty obtained for the sample B2##. These results are the average of the three or four (depending on the sample) measurements taken on each sample. They are analysed in the following section.

Table 2

Sample	focal length (mm)
B210	2.71±0.1
B220	2.65±0.1
B230	2.60±0.1
B240	2.50±0.1

3-Analysis

Now we compare the results that have been obtained with the perfilometer and the optical microscope with the ones obtained with the spherometer (Chapter A), they should be almost the same. To make this comparison we have gathered in the tables below (3 to 6) the largest and the smallest focal length calculated with the results of the perfilometer, then the results obtained with the spherometer and finally the difference in percentage between the two closer results.

Table 3

Sample *B210*			
f min (mm)	**f max (mm)**	**f spherometer (mm)**	**spacing**
2.60	2.69	2.70	0.5%

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Table 4

Sample ***B220***			
f min (mm)	**f max (mm)**	**f spherometer (mm)**	**spacing**
2.40	2.64	2.65	0.5%

Table 5

Sample ***B230***			
f min (mm)	**f max (mm)**	**f spherometer (mm)**	**spacing**
2.18	2.46	2.60	5.8%

Table 6

Sample ***B240***			
f min (mm)	**f max (mm)**	**f spherometer (mm)**	**Spacing**
1.79	2.36	2.50	5.7%

In these tables appears clearly that **the measurements taken with the spherometer are larger than the ones taken with the perfilometer**. Moreover this difference gets larger and larger when the diameter of the beginning hole increases. So that we think this difference is mostly due to the fact that **the micromirrors are not perfectly circular** (they are less and less circular when the diameter increases) that leads to an uncertainty on the focal length.

Nevertheless, even if we consider all these uncertainties, **it remains a difference**, for example on the sample B240 this difference δ is about $\delta = 2.50 - 2.36 = 0.14mm$ and we do not really explain this difference. It is probably due to the spherometer and an underestimation of the uncertainty but we could never prove it.

Conclusion

This method using a spherometer is really simple to measure the focal length, even for very small samples, however **the results obtained are not really coherent with the ones given in the chapter A**. It should mostly be due to **the imperfect shape of the micromirrors** and probably also to the method itself but we could not point out precisely the problem. Whatever, all this work enlightens **the huge importance of the circularity of the micromirrors**, we think that at least the parameter of circularity (cf. chapter A II 2) should be of 2%. We will really take care of it in the following sections and especially in the one concerning the applications of micromirrors.

E. Dalimier
G. Lecamp

Introduction

In Chapters A, B, C were given the results obtained with different methods, concerning the diameter, the circularity and the focal length of a set of micromirrors coming from different pinhole sizes. It appeared then necessary to compare these results and present a definitive characterisation of the micromirrors.

Thus the following parts compile all the results concerning each of the parameters quoted above.

I Measurement of the diameter and the circularity

The diameter was only measured with the optical microscope, there is no comparison to be done with other methods. As this simple method can definitely be assumed as reliable, this is not a problem.

Here is a table summarising the results for both the diameters and the circularity of the samples (this last parameter comes from the diameters as seen in Chapter A, part II.).

Pinhole size (microns)	angle	Diameters (microns)	stand dev	uncertainty	parameter of cicularity
10	0°	303	1.7%	3.3%	1.6%
	45°	308	1.6%	3.2%	
20	0°	415	1.2%	2.4%	3.6%
	45°	430	1.2%	2.3%	
30	0°	483	2.1%	2.1%	5.7%
	45°	512	2.0%	2.0%	
40	0°	499	0.8%	2.0%	12.9%
	45°	572	1.2%	1.7%	
50	0°	508	1.2%	2.0%	17.9%
	45°	620	1.6%	1.6%	

Table 1. Diameters and circularity

As it was said in Chapter A, Part II., the standard deviation always remains below the uncertainty calculated, and thus enhances the very good repeatability : from 0.8% to 2.1%.

As for the circularity, we can consider the samples of 10 microns pinhole size as circular, even though the diameter slightly differs from a direction to the diagonal one. This difference grows with the pinhole size, and so does the parameter of circularity, up to about 18% for the bigger samples.

E. Dalimier
G. Lecamp

II Measurement of the focal length

Two different methods were used to determine the focal length of the micromirrors. One was to calculate it from the measurement of the sagitta and the diameter, and the other was to measure it directly.

1-Calculation

As seen in Chapter A, Part III., it is possible to calculate the focal length from the diameter and the sagitta of the micromirrors.

In parts A and B were presented the measurements of the sagitta, with the perfilometer and the interferometric microscope. Let us remind here the results obtained with the two methods.

Table 2. Measurement of the sagitta

	perfilometer		interferometric microcope		
	Average (microns)	Stand dev	Average (microns)	Stand dev	uncertainty
sample 10	4.4	2.3%	4.4	3.2%	6.4%
sample 20	8.9	2.2%	8.9	1.9%	3.1%
sample 30	13.2	1.5%	13.2	1.9%	2.1%
sample 40	17.3	2.3%			
sample 50	21.2	1.9%			

It may be useful to remind that the uncertainty for the perfilometer was assumed to be part of the standard deviation (or else negligible), so it does not appear in Table 2. As for the uncertainty of the interferometric microscope, it is always larger than the standard deviation.

Both methods present exactly the same results for the value of the sagitta, and quite the same results for the standard deviation. Therefore the measurement of the sagitta can definitely be presented as reliable.

The other parameter necessary for the calculation of the focal length is the diameter. As seen in Part I, there are two values for each sample kind. Therefore, there is not one reliable value for the focal length but a whole range of values limited by the two values calculated from the two diameters. This is shown in Table 3.

Table 3. Calculation of the focal length.

pinhole size (microns)	sagitta (microns)	diameter (microns)	focal length (microns)
10	4.4	303	1300
		308	1350
20	8.9	415	1210
		430	1300
30	13.2	483	1100
		512	1240
40	17.3	499	900
		572	1180
50	21.2	508	760
		620	1130

This uncertainty on the focal length leads us to think that only the micromirrors of 10 microns pinhole size, and to a lesser extent the micromirrors of 20 microns pinhole size, are usable. As for the other micromirrors, it appears necessary to let them in the KOH solution a longer time.

2-Direct measurement

Another method to obtain the focal length was explained in Chapter C, with the spherometer. What has to be remembered is that the results were not coherent, as the focal length measured was always above the range of values calculated, with a difference going from 0.5% to 6% with the largest value of the range. We did not find any failure in the calculation methods of the focal length, whereas because of the adjustments problems, some doubts exist concerning the spherometer. Therefore, the spherometer results will not be taken in account.

Moreover, this method, simple in theory, implies a long time for adjusting the optical system, thus we can only point its pedagogical interest by lack of its accuracy for our study.

Conclusion

E. Dalimier
G. Lecamp

To conclude on this study, we can first definitely point out the very good repeatability on the fifteen samples of each kind: the standard deviation on the diameter and the focal length never exceeds 3.3 %. The important problem remains the square deformation of the micromirrors, which implies a large uncertainty on the focal length. This can only be solved by an addition time in the KOH solution.

The use of several methods helped to compare and valid the results. It also had a pedagogical impact as it enabled us to compare the simplicity of utilization as well as the uncertainty on each method. Hence, the spherometer, based on a simple optical system, did not appear very reliable for the focal length. Concerning the perfilometer, it had a better precision and it was simpler to use than the interferometric microscope, thus it is preferable.

E. Dalimier
G. Lecamp

Introduction

In the former parts, we have characterised five different kinds of micromirrors and pointed out their repeatability. We can now focus on their possible utilisation in optical systems, compare them, and enhance the problems implied in the fabrication process. Here are presented two different simulations made with OSLO of "4f systems" very useful in telecommunication, as well the "ended-ended" systems correspondent.

I Foreword on the systems

1-Utilisation of the micromirrors

What has to be pointed out is that the micromirrors characterised must be used as convergent mirrors (or lenses). Indeed, if we use the transparency of the silicon in the IR, light will meet the convex etched forms in the divergent way, and prevent from focusing, as shown below in the Figure1.

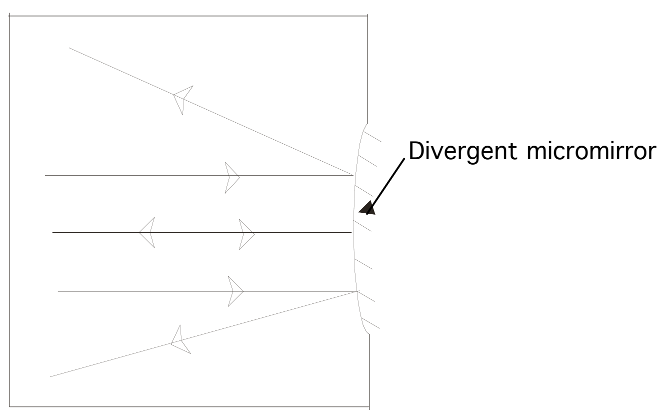

Figure1. Divergence of the micromirrors in the silicon.

Therefore, we thought of different solutions that are presented below: the first one is the one inspired by Raul, with a glass layer above the silicon, and the second one uses the micromirrors as templates for a plastic material.

2-Choice of the micromirrors

As we have seen in the former parts, the bigger the micromirrors are, the more the uncertainty on the focal length grows (because they are not circular enough).

Nevertheless, because of the source (as seen later on in part I.3-), a certain minimum diameter is definitely needed. Compromising on these two parameters, we chose to design our systems with micromirrors coming from 20 microns pinholes.
Therefore, the accurate data that will be used later in the calculations are

Diameter **D = 420 microns**
Sagitta **s = 8.9 microns**
Focal length **$f = D^2 / 16s = 1239$ microns**

We had two values for the diameter (coming from the square deformation), so the average of them was chosen, and this gave an average but arbitrary value for the focal length.

It is important to note, though, that for the oral presentation on the 26 of July, the systems were presented with micromirrors coming from 10 microns pinhole sized.

3-Choice of the source

In order to precise the designs, it was necessary to work with a determined source of light. According to the size of the micromirrors, it appeared relevant to choose a laser source, defined as a beam of 200 microns of diameter. This conventional source explains the necessity of a diameter larger than 300 microns. The OSLO simulations were made with a wavelength of 588 nm. These parameters are important as they determine the angles and indexes of the simulations, as we will see later on.

II System with a glass layer

1-Calculation of the system

a) Presentation of the system

After having talked to Raul, we studied the system, shown in Figure 2, he had thought of. This system includes a glass layer, which is put directly on the micromirrors. For the simulation, the KF3 glass was chosen, having a refractive index equal to 1.51 at the wavelength chosen (588 nm). A reflective layer must be deposited on a part of the upper edge of this glass layer in order to make the beam reflect on the second micromirror.

We use this system as an infinity-infinity combination, so the image focal point of the mirror *M1* (and the object focal point of the mirror *M2*) must be on the reflective part of the reflective of the glass layer (mirror *M3*).

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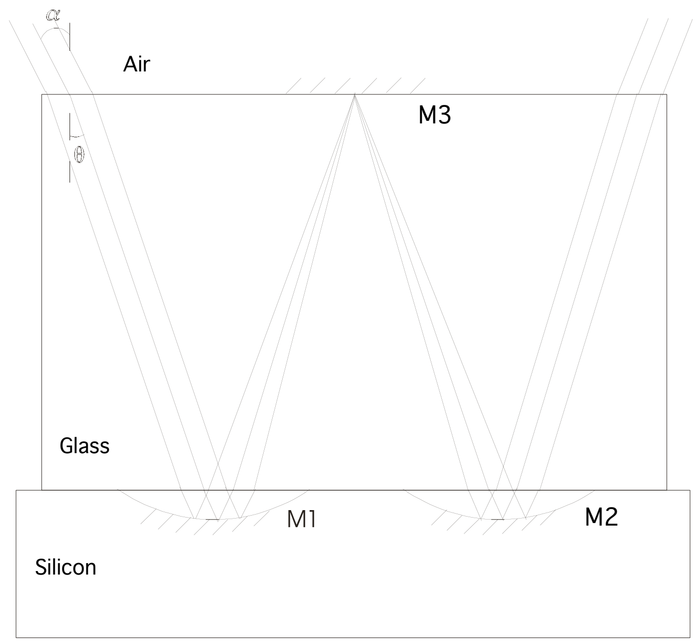

Figure 2. System infinity-infinity with a glass layer.

At this point, we can define and calculate the different parameters: the thickness of the glass layer, the spacing between the micromirrors, and the entrance angle.

b) Calculation of the thickness

For the calculation of the thickness *t*, we must not forget the thin layer of air between the mirror and the layer of glass.

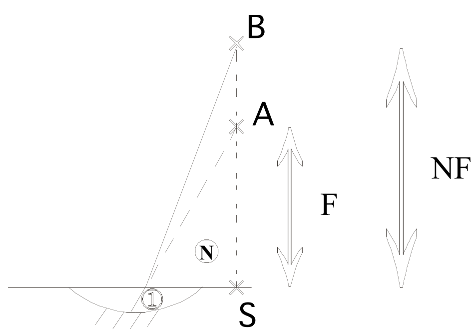

Figure 3. Calculation of the thickness.

As seen on the Figure 3, the beam coming from the infinity on the mirror will focus at a distance *f* (the focal length) from this mirror at a point *A*. Then the image of *A* by the diopter which separates the air (index 1) from the glass (index n) is *B*. The formula of this conjugation is

$\overline{SB} = n \cdot \overline{SA}$, *n* being the index of the glass.

Therefore, the thickness of the glass layer must be **t = *nf***.

c) Calculation of the field angle and the arrangement of the mirrors

We tried several combinations with different distances between the micromirrors and different angles.

The distances are a compromise between being the aberrations problems (the smaller the spacing is, the fewer there are aberrations) and the fabrication possibility (so that the micromirrors do not mix together). We chose to present systems with a distance edge to edge between the micromirrors of 50 and 100 microns.

For each spacing, the two different angles were chosen to get the “limit case” when the whole beam just hits the second mirror after reflection on mirror M3, and the “centered case” when the middle of the beam hits each mirror on the center.

For each simulation, we calculated the angles θ and α as well as the arrangement of the mirrors, this is to say three distances: the distance between the middle ray of the beam at the entrance on the glass layer and the center of the mirror *M1* (named *a* on the Figures 4 and 5), the spacing between the center of *M1* and the image focal point on *M3* (named *b* on the Figures 4 and 5), and finally the spacing between this last point and the center of the mirror *M2* (named *c* on the Figures 4 and 5). The calculation of these distances only helps for the OSLO simulation, but they are not optically relevant.

α) The “centered case”

For the “centered case”, the calculations are simple, when we look at the Figure 4.

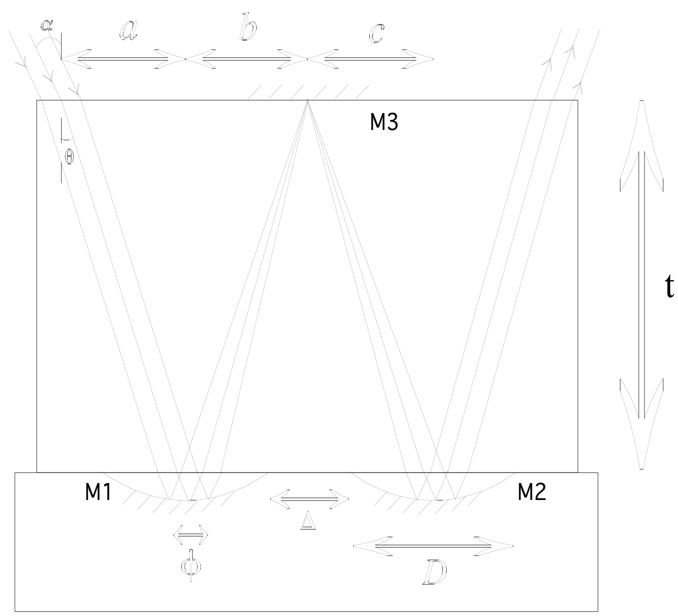

Figure 4. Calculations for the “centered case” of the system with a glass layer.

Here we want that the middle ray of the beam hits each of the mirrors *M1* and *M2* on the center, as we can see on Figure 4. This middle ray hits and is reflected by the two mirrors with the same angle α as when it enters the glass layer. Then it turns to θ again, just after the reflection, on the surface of the diopter seen on Figure 3. Therefore, as the distance run with the angle α is far smaller than the one run with the angle θ (about 9 microns out of nf = 1871 microns), we can do an approximation. It will be considered for the calculations that the middle ray reflects on the 3 mirrors with the angle θ.

Following on the Figure 4 the middle ray from its reflection on *M1* and until it reaches *M2*, we have

- $tan\theta = \frac{D+\Delta}{2nf}$, where *D and Δ* are the parameters defined on the Figure 3

(*D* is the diameter of the micromirrors and *Δ* the spacing between them from edge to edge)

- $sin\alpha = nsin\theta$

- $a = b = c = nf \cdot tan\theta$

β) The "limit case"

The "limit case" corresponds to the minimum field angle, which prevents from parasite reflections: the beam hits the two micromirrors and not the silicon in between, as shown on Figure 4.

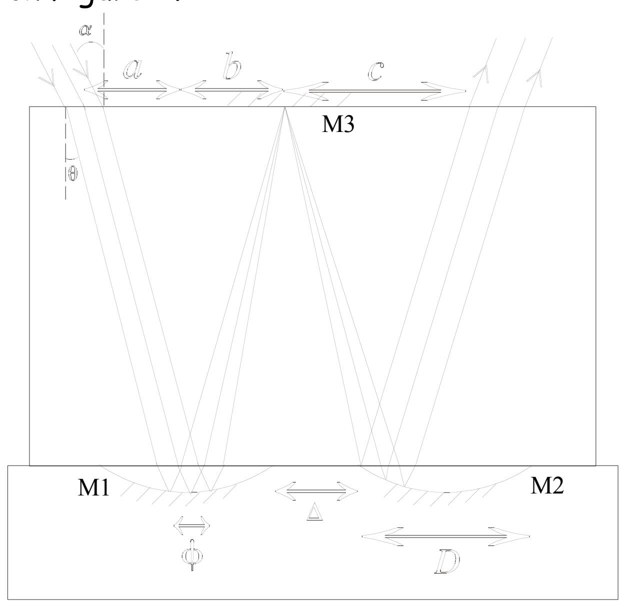

Figure 5. Calculations for the "limit case" of the system with a glass layer.

Here, we have to take in account the diameter of the beam (Φ on the Figure 5), and the calculations are a bit more complicated. We keep on following the middle ray and we assume that when the beam hits *M2*, it still has the same diameter ϕ. Therefore, we have the following formula,

- $tan\theta = \dfrac{D/2 + \Phi/2 + \Delta}{2nf}$
- $sin\alpha = nsin\theta$
- $a = b = nf \cdot tan\theta$
- $c = (D + \Delta) - b$

All these results can be summarized in the Table 1, depending on the spacing Δ and the case studied.

spacing (microns)	case	theta (degres)	alpha (degres)	distance (microns)		
				a	b	c
100	limit	6.3	9.5	205	205	315
	centered	7.9	12.0	260	260	260
50	limit	5.5	8.3	180	180	290
	centered	7.2	10.9	235	235	235

Table1

The OSLO simulations for each case can be found in Appendixes 10, 9, 8, and 7 (in the inverse order than in the Table 1). We entered the data calculated as seen above.

2-Discussion on the system

Considering the OSLO simulations, we can firstly point out that the approximations made were justified. Indeed, the angles as we calculated them seem to fit perfectly. In fact, we realized that this parameter is not sensitive, since a change of 0.5° is not perceptible for the “limit case” for example.

The different cases studied enable us to have an idea of the range of incident angle possible, the minimum and the “middle” one. We can see here that the angle θ varies of about 1.6° between the limit and the centered case (meanwhile, α varies of 2.5°). As for the difference of spacing Δ, it causes a variation of about 1°. Nevertheless, all these data remain under 12°, which can be considered as a small angle and will not generate much aberration.

As the system seems to work, we can though highlight some possible problems which must not be neglected. Indeed, because of the diopters glass/air, parasite reflections will exist (about 4%), and imply a loss of intensity. The thickness of glass (about 1900 microns as seen above) can also generate aberrations. It would have been accurate to study exactly the aberrations of this system, but a lack of time prevented us from doing it.

III System F

1-Calculation of the system

a) General idea

The following idea is really simple, in fact since (cf. Chapter C I) the micromirrors made using the etching method with KOH cannot be directly used because they are divergent, **they can be used as templates**. We put on them a transparent plastic with an index different from 1 and we obtained convergent micromirrors (cf. figure 1) which are much more useful.

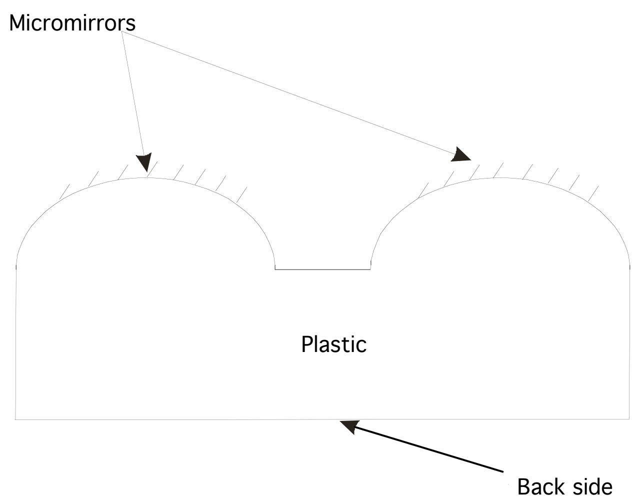

Figure 6: The plastic convergent micromirrors

Then we have to calculate the different parameters (thickness, distance between the two micromirrors...) to design a 4f system and a system "ended-ended".

b) Calculation for the 4f system

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For this system we have designed one example with a spacing between the two mirrors of 50□m and the beam hitting the middle of the mirror M2 (cf. Appendixes 12 and 12'), one with a spacing between the two mirrors of 50□m and the beam hitting the edge of the mirror M2 (cf. Appendixes 11 and 11'). And the same ones with a spacing of 100□m (cf. Appendixes 14, 14', 15 and 15').

The first important parameter is **the thickness of the plastic, t.** At the entrance of the system arrives a parallel beam and we want at the exit a parallel beam, so the beam must focus on the backside (cf. Figure 6), i.e. the thickness must simply be the focal length, f.

Then **the distance □ edge to edge between the two micromirrors**. The thing to keep in mind is that the larger this distance will be, the larger the angle will be (more aberrations); so that we tried to minimise it. Nevertheless the mirrors should not be to close otherwise the system would be impossible to fabricate. A good compromise is a distance □ between 50□m and 100□m.

Finally **the entrance angle □**. The problem is that after the second reflection on the backside, the whole beam should at least hit the edge of the mirror.

α) The beam hit the edge of the mirror M2

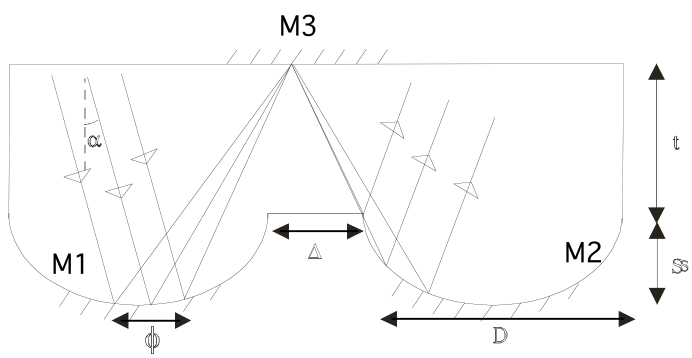

Figure 7: Sketch of the 4f system (limit case)

The calculation of the entrance angle α is almost the same as the one in the section Chapter E II 1 c), the single difference is the thickness which is the focal length in this section.

For the other parameters, this is the same, we have the same approximation (the diameter of the beam remains the same on the mirror M2) and the same formula $tan\alpha = \dfrac{\dfrac{\phi}{2} + \dfrac{D}{2} + \Delta}{2.f}$.

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So it is possible to calculate this angle α and make the OSLO simulations (cf. Appendixes 11, 11', 14, and 14').

β) The beam hit the middle of the mirror M2

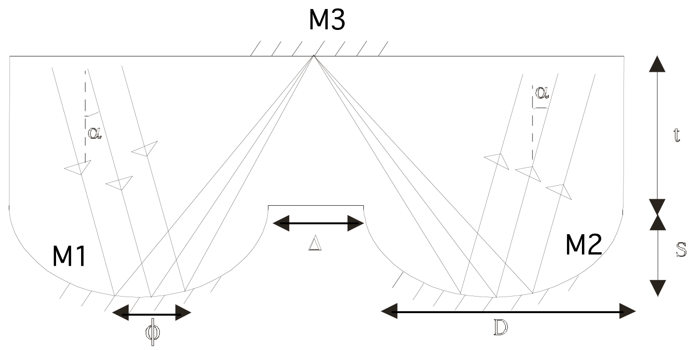

Figure 8: Sketch of the 4f system (centre case)

The calculation for this system is almost the same as the one in the former section, the formula is $tan\alpha = \frac{\frac{D}{2}+\frac{\Delta}{2}}{f}$. Then we can simulate the system with OSLO (cf. Appendixes 12, 12', 15 and 15').

γ) Numerical calculations

All the results of these calculations are gathered in the table 2, which gives the entrance angle α and the thickness t, depending on the system. **The thickness indicated is the one calculated after an optimisation with OSLO**. In fact because of the aberrations our theoretical calculations do not give a perfect focalisation on the willing point, that is the reason why we modify the thickness t, with OSLO to obtain the satisfying focalisation. For example, for the 4f system with a spacing of 100 microns between the two mirrors in the centre case, the calculation gave a thickness t=1.248 mm and after an optimisation with OSLO, we found t'=1.180mm, this last value is the one we have kept.

E. Dalimier
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spacing (microns)	case	alpha (degrees)	Thickness (mm)
100	limit	9.4	1.20
	centered	11.9	1.18
50	limit	8.3	1.21
	centered	10.7	1.22

Table 2

c) Calculation for the system "ended-ended"

The first parameter to calculate is again the thickness of the plastic layer, the condition is to have the object and the image on the surface of plastic (cf. Figure 9)

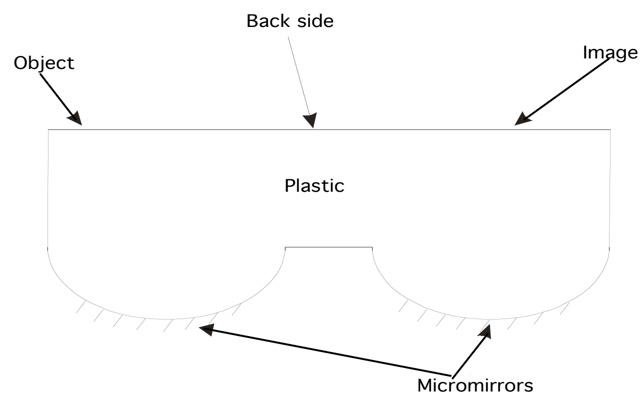
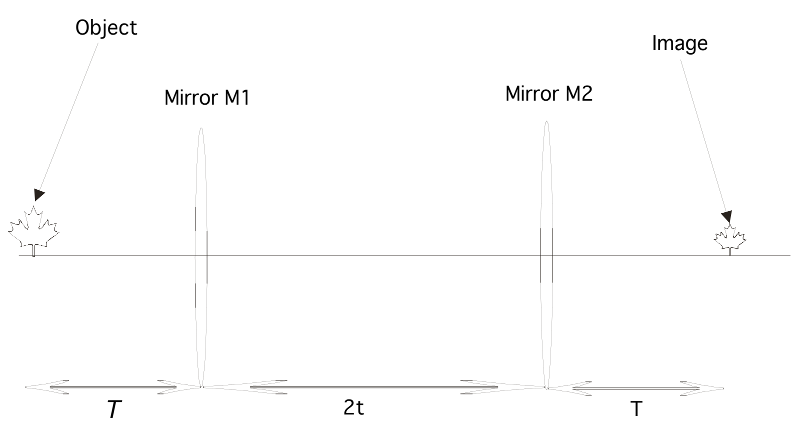


Figure 9: Placement of the object and the image.

To understand better the problem, we unfold the system (cf. Figure 10) thus we obtain a more usual one on which it is easier to work on and especially to make the calculations.



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G. Lecamp

Figure 10: The unfolded system.

Intuitively the thickness is $t = f'$. Indeed the object is on the object focal plane of the first lens so that its image is at the infinity, then the image of the infinity through the second lens is at the image focal plane, i.e. on the plastic layer, since $t = f'$, exactly what we wanted.

For the distance between the two mirrors, we still worked with 50μm and 100μm.

Finally the entrance angle does not exist because the object is not at the infinity but we have to determine the position of the object. At first, since our object is a pinhole and so there will be a lot of diffraction, **we could put the object anywhere on the plastic layer**. Nevertheless the best solution would have been to realise a photometry study on the system and to determine in which position of the object, the image is the brightest but we did not have enough time and software to do it. We decide to **put the object arbitrarily at L=200μm of the centre of the first micromirror** (cf. figure 11).

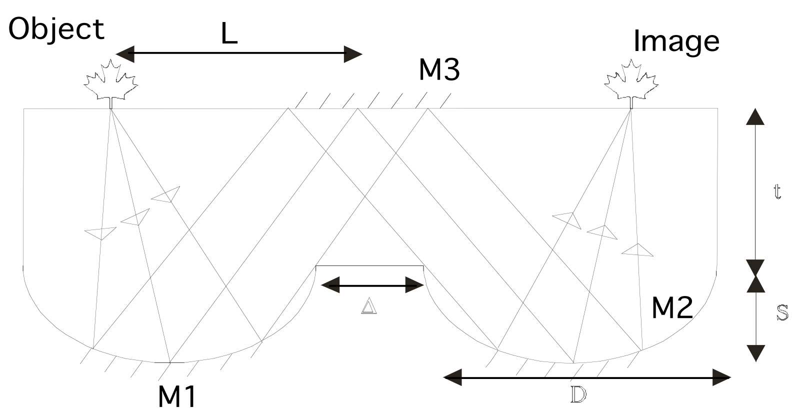


Figure 11: The "ended-ended" system.

2-Discussion on the system

This system is certainly **the simplest** on its background idea and conception. The only problem is the realisation of the plastic micromirrors, in fact the quality of the deposit must be sufficient not to affect the optical quality of the mirrors. Moreover these systems are more **compact and simpler** than the one with the glass layer. Last but not least the same design **can be used whether as a 4f system or as an "ended-ended" system**, this general-purpose is really important and very handy. An even more compact system (a f/3 system) is possible if the beam reflects three times instead of one on the M3 mirror (cf Appendix 17) but the angle is too important because of the size of the micromirrors, so we are worried about the aberration and we prefer not to work on it.

The only reserves on these systems are the aberration and photometry study that has not been done. Intuitively, as the angles are smaller than 12 degrees, we can hope that the aberrations will remain negligible, i.e. they will not affect too much the quality of the image. However the results concerning the photometry study are difficult to predict, either a simulation or an experimental series should be led.

Conclusion

To conclude on this section about the different optical systems realisable with the micromirrors studied in the first part of our workshop, we have to choose the best one. **The criteria are the size of the system, the quality of the image and the simplicity**. The system based on plastic micromirrors seems to check, at best, these properties.

The only regret is the fact that we do not have enough time to test and check our simulations but the following will have to work on this experimental study and confirm or cancel our conclusions.

E. Dalimier
G. Lecamp

General conclusion

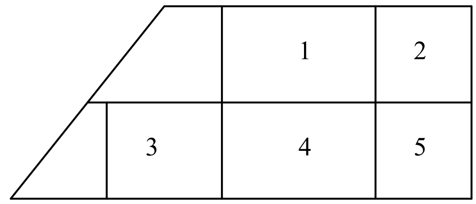
This study on micromirrors was, for us, the occasion to work on a new part of optics, the miniaturised optics. We have worked on two different parts, the characterisation of micro-optics and then the design of micro-optical systems.

The first part of our work permited us to study the characteristics of the micro-mirrors and the repeatability of the fabrication process (etching with KOH). The conclusions are clear: the method is really repeatable, but the circularity of the mirrors and so the determination of the focal length, is not good enough to use them in a micro-optical system. The solution is probably to lengthen the duration of the etching in the KOH solution.

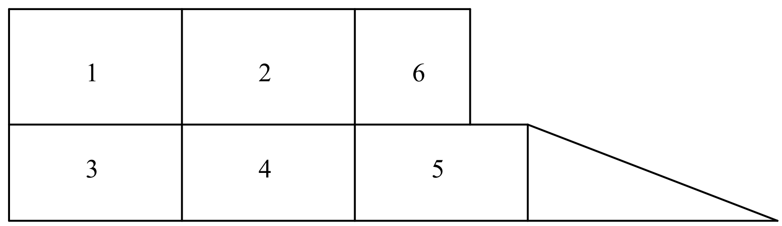
Concerning the design part, we tried to imagine two kinds of systems: a 4f system useful for telecommunications and an ended-ended system. We have worked a lot on OSLO to check our theoretical calculations by simulations. Overall the simulations confirm them but the photometry study has not been done so we prefer to be careful on the results. We would really have liked to do the experimental tests on the systems and to check definitely our assumptions but our workshop was too short.

E. Dalimier
G. Lecamp

Sample A :



Sample B :



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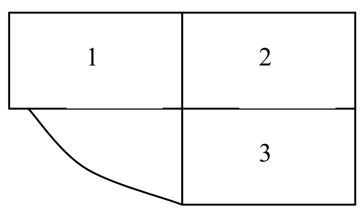
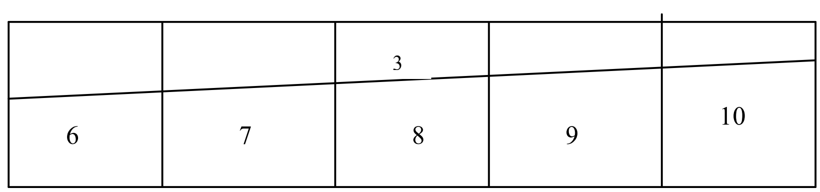
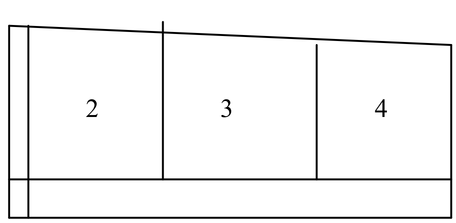


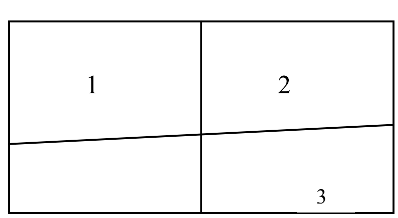
Sample D :



Sample E :



Sample F :



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Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	sagitta 4
A110		4.392		4.350		4.327	4.382
A110 a 90°		4.288		4.323		4.293	4.368
A310		4.337		4.312		4.389	4.403
A410		4.138		4.209		4.170	4.215

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
A120		8.712		8.762			**8.762**
A320		8.752		8.722			**8.752**
A420		8.762		8.941		8.724	**8.941**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
A130		12.99		13.01			**13.01**
A330		13.59		13.59			**13.59**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
A140	565.000	16.85	565.00	16.70	565.00	16.78	**16.85**
A240	600.000	16.83	600.00	16.58			**16.83**
A340	575.000	17.26	570.00	17.40	570.00	17.38	**17.40**
A440	580.000	17.58	585.00	17.61	580.00	17.24	**17.61**
A540	580.000	16.940	580.000	17.100	580.000	16.960	**17.100**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
A150	615.000	21.03	620.00	21.45	610.00	21.15	**21.450**
A250	610.000	20.260	610.000	20.410			**20.410**
A350	610.000	21.400	615.000	21.990			**21.990**
A450	620.000	21.560	610.000	21.400			**21.560**
A550	620.000	21.410	620.000	21.460			**21.460**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
B130	485	13.67	485	13.65			**13.67**
B230	490	13.18	490	13.2	490	13.03	**13.2**
B430	490	13.01	500	13.02	485	13.1	**13.1**
B530	490	13.29	490	13.45	490	13.44	**13.45**
B630	485	13	485	13.13			**13.13**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
B140	580	17.63	570	17.46			**17.63**
B240	575	17.45	580	17.47			**17.47**
B440	575	17.45	580	17.68			**17.68**
B540	580	17.17	570	17.05			**17.17**
B640							

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
B150							
B250							
B450	625	20.87	615	20.99			**20.99**
B550							

B650							

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	max
C140		1.459		1.574			**1.574**
C220		8.735	415.000	8.855	405.000	8.705	**8.855**
C230	480.000	13.030	480.000	13.070			**13.070**
C240	560.000	17.260	585.000	17.150			**17.260**
C310	305.000	43.410		45.090			**45.090**
C350	605.000	20.990	605.000	20.890			**20.990**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	max
D310							
D710	304	4.441	304	4.553	302	4.491	**4.553**
D810	302	4.098	298	4.144			**4.144**
D910	296	4.145	296	4.144			**4.145**
D1010							

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	max
D320							
D720							
D820	420	8.721	415	8.719			**8.721**
D920	420	8.971	425	9.759	420	8.977	**8.971**
D1020	425	8.505	400	8.66	410	8.507	**8.66**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	max
D330							
D730							
D830							
D930	490	13.27	485	12.75	490	13.22	**13.27**
D1030	485	12.93	475	12.73	470	12.84	**12.93**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	max
D340							
D740							
D840							
D940	505	17.94	510	17.82	505	17.47	**17.94**
D1040	505	16.11	515	15.93	505	16.42	**16.42**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	max
D350	505	20.79	510	20.83			**20.83**
D750							
D850							
D950	520	21.39	510	21.63	515	21.54	**21.63**
D1050	515	20.45	510	20.2			**20.45**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	max
E210							

E. Dalimier
G. Lecamp

E310							
E410	308	4.430	310.000	4.499			**4.499**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
E220	425	9.115	420.000	9.134			**9.134**
E320	440	9.286	450.000	9.538			**9.538**
E420	420	8.809	425.000	8.750			**8.809**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
E230	490	13.310	490.000	13.380			**13.380**
E330	485	12.770	490.000	13.000			**13.000**
E430		13.400	490.000	13.220	500.000	13.380	**13.400**

Sample	diameter 1	sagitta 1	diameter 2	sagitta 2	diameter 3	sagitta 3	**max**
F140	500.000	17.960	500.000	17.830			**17.960**
F220	405.000	8.395	405.000	8.350			**8.395**