

Criterion to appreciate difficulties of Aspherical polishing

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ABSTRACT

The increase of optical resolution and size of astronomical telescopes needs to:

- 1) Improve surface quality of optical components
- 2) Use more and more complex aspherical shape for lenses and mirrors

Due to these 2 constraints, the optical manufacturers had to improve their equipments such as the Computer Controlled Polishing and to appreciate the feasibility of very complex aspherical shape. Concerning this second point, we propose a new criterion based on surface definition, on quality specification for the polishing and on limitations of equipments. Manufacturing examples show that this criterion is well representative, and particularly for direct off-axis polishing.

Key-words: Aspherical Optic, Criterion, Off-axis Polishing, CCP Finishing.

1. INTRODUCTION

For 20 years, a lot of improvements have been made in optical manufacturing including production of aspherical components. From now on, it is clear that aspherical components become part of high tech optical systems (mirrors and lenses). So it is important to have some guidelines to use aspherical components in optical design calculation. We will introduce a new criterion as help for the designer taking into account the current technologies for aspherical polishing.

2. HISTORY

The main criterion used up to now to compare aspherical surface was the Mercier's criterion ^[1]. Along the radial profile of the surface, it gives the minimum length δy for which the aspherical surface can be estimated with a sphere without error greater than $\lambda/4$ (which is the Marechal' law for good image quality):

$$\delta y = \frac{N^3}{4 \times Cc}$$

N: numerical aperture Cc: conic constant

Note: the same criterion is used with a different factor ($8 * N^3 / Cc$) in other comparisons studies ^[2].

This criterion was established for polishing with large tools, which made only radial profile correction of the aspherical shape. It didn't take into account neither the flatness quality requested on surface, nor the Computer Controlled Polishing (CCP) systems used for finishing.

Since 1995, we used CCP for aspherical components and during 2001, we had also developed specific tools and processes in order to be able to polish direct off-axis aspherical surface. In that case, the Mercier' criterion could not be used because polishing was not only a profile correction. Also we adapted the existing criterion to propose a new one.

3. CCP LIMITATIONS

We can classify the CCP equipment in 4 families:

- Mechanical CCP, a small polishing tool is moved on the surface ^[3],
- Ion beam CCP, an ion beam is used to remove the glass ^[4,5],
- Fluid jet CCP, an abrasive fluid makes the removal ^[6],
- Magnetorheological CCP (patented), a magnetorheological fluid is used as polishing tool ^[7].

For all this systems, the trajectory is calculated in order to correct the surface flatness using the dwell time law as guideline.

Limitations of these equipments are induced by:

- Accuracy of interferometric measurements used to make trajectory calculations.
- Solving the trajectory calculation (the deconvolution between removal volume desired and removal law of the tool in order to obtain the trajectory of the tool). It affects particularly the edge of the component.
- Repeatability of removal law of the tool is limited by the tool and by the surface shapes:
 - The first point is the result of the type of CCP and creates advantages and drawbacks for each CCP process.
 - The second point is the cause of the fluctuation (predictable or not) of the removal law due to the surface shape fluctuation. It is mainly linked to the aspherical equation and it will be a part of the criterion.
- Size and geometry of the polishing tool. It defines the removal law, and therefore the trajectory. If we compute the spatial frequencies of the irregularities on the optical surface, we can separate them in 3 parts according to the tool dimension:
 - Low spatial frequency defects (as irregularities often identified in optics by the 36 first Zernike coefficients), they are mainly corrected by CCP (main drivers of the tool trajectory)
 - Frequency defects in the same range than tool diameter: they can be corrected nor by trajectory neither by tool definition (solution for example will be to manage different tools dimensions).
 - High spatial frequency defects: quilting (for lightweighted mirror), ripple (initiated by the aspherical grinding or by the spiral trajectory of CCP tool), roughness, local defects. The capability to smooth high frequency irregularities is mainly dedicated to mechanical polishing tool like:
 - Small rigid mechanical tool moved by CCP.
 - Big tool moved by traditional polishing equipment.
 - More complex mechanical tools ^[8].

4. LOCAL DEFINITION OF ASPHERICAL SURFACE

Taking into account that all CCPs use small tool, it is important to have a good view of the optical surface shape as seen by the tool. If the optical surface has a diameter \emptyset , an aspherical shape defined by a radius R and a conic constant Cc , the parametric equation of the surface is:

$$Z(r) = \frac{r^2}{R \times (1 + \sqrt{1 - (1 + Cc) \times \frac{r^2}{R^2}})}$$

With r a radial position.

The radii of this surface at r are:

$$\text{Meridian radius: } Rm(r) = R \times \sqrt{(1 - Cc \times \frac{r^2}{R^2})^3} \qquad \text{Tangential radius: } Rt(r) = R \times \sqrt{1 - Cc \times \frac{r^2}{R^2}}$$

4.1 Analysis of radii variations

Both radii are changing along the radial profile of aspherical surface. For example (figure 1) for a parabola, the fluctuations at the edge are according to its F-number:

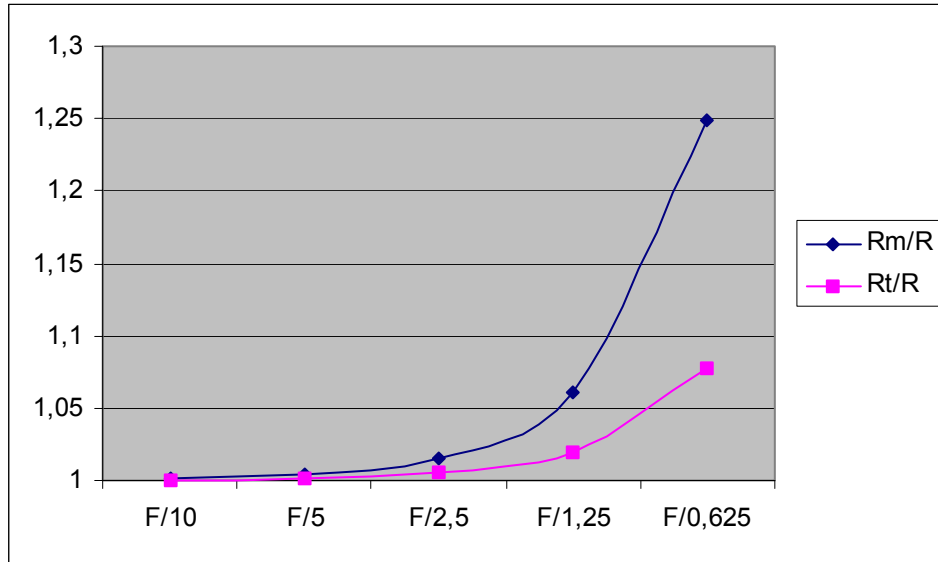


Figure 1: Ratio of radii according to F-number

The meridian radius is bigger than the tangential radius if the conic constant is negative. Difference between radii is bigger and bigger as radial position increases: locally the surface becomes more and more toroidal.

4.2 Analysis of sag values under the tool

If T is the tool diameter and if it is small, we can assume that under the tool, the optical surface is a toro defined by both radii R_m and R_t (figure 2).

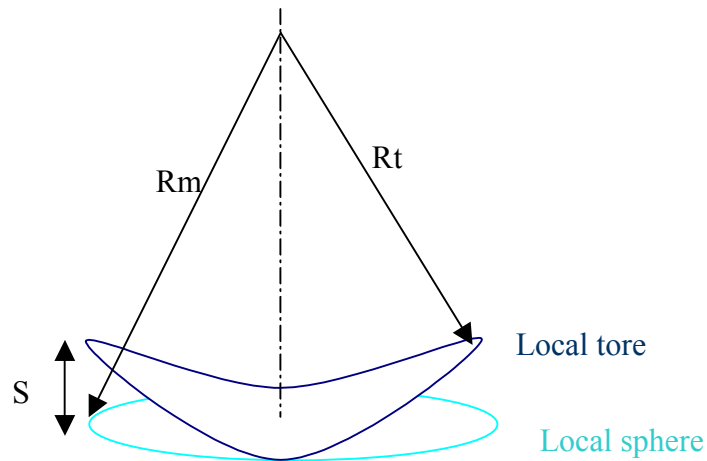


Figure 2: local view of aspherical surface

Looking to this tore, we can compute the sag S between both radii under the tool, which is (as $T \ll R$):

$$S(r) = \frac{-Cc \times T^2 \times r^2}{8 \times \sqrt{(R^2 - Cc \times r^2)^3}}$$

T diameter means representative diameter according to each type of CCP process. CCP manager taken into account the removal law under the tool must define this T parameter.

If we calculate also the sags variations for each axis between the centre of surface ($r = 0$) and a position r:

$$\delta Sm(r) = \frac{T^2 \times ((R^2 - Cc \times r^2)^{1.5} - R^3)}{8 \times R \times (R^2 - Cc \times r^2)^{1.5}}$$

$$\delta St(r) = \frac{T^2 \times (\sqrt{R^2 - Cc \times r^2} - R)}{8 \times R \times \sqrt{R^2 - Cc \times r^2}}$$

4.3. Analysis of sags variations

For example for a parabola surface, the sag variations of the local tore versus the size of the tool are:

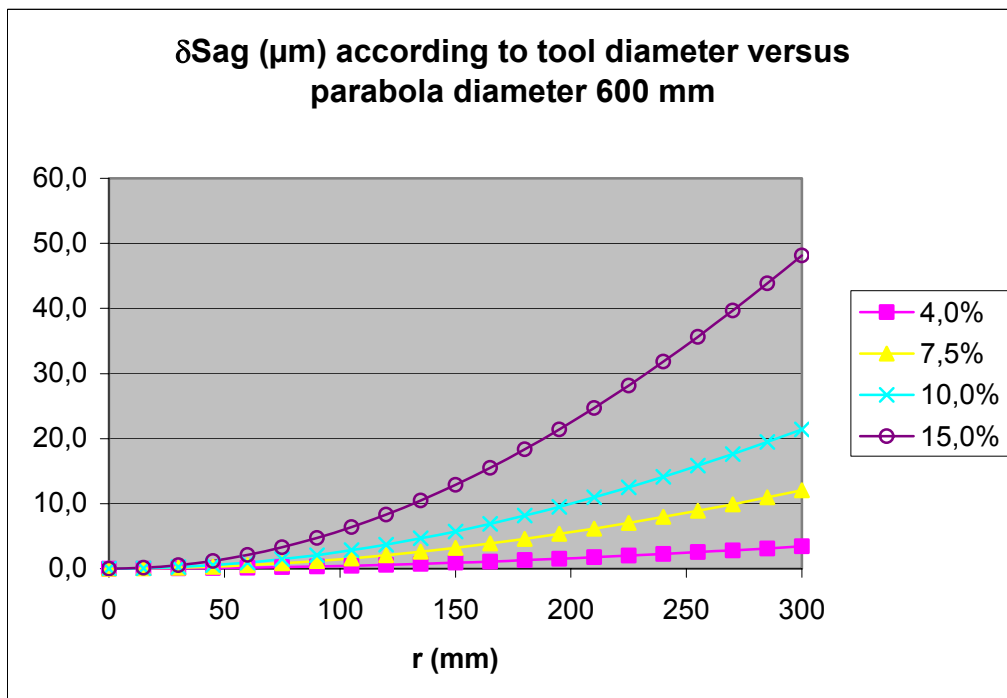


Figure 3: Local sag versus tool diameter

As seen on this figure 3, for a F/1 component and a tool with diameter 10% of the component diameter, local tore has a difference of sag, which is bigger than 10 µm.

If we compare for the same component:

- Local differences due to meridian and tangential radii
- Difference between Meridian radius and radius in the centre
- Difference between Tangential radius and radius in the centre

We find the following graph (figure 4):

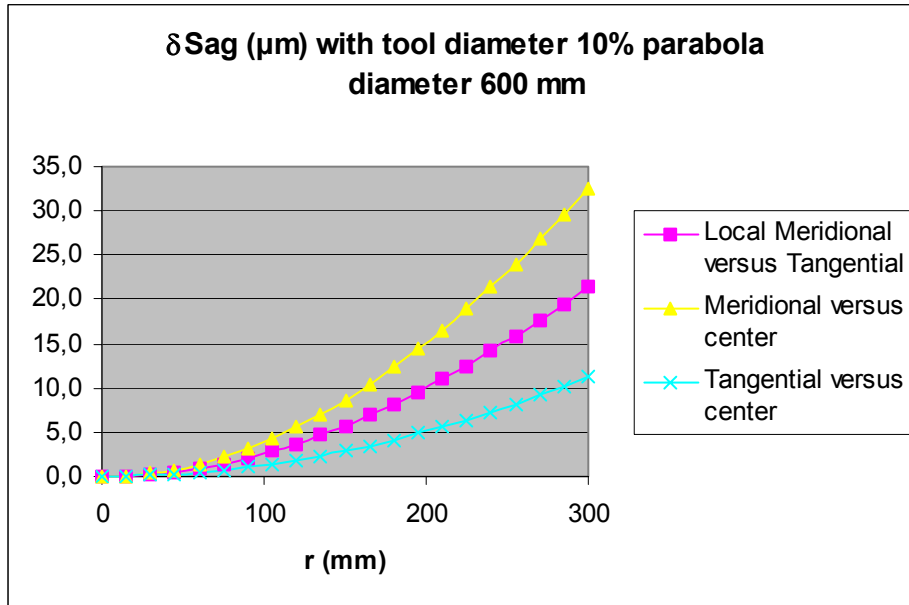


Figure 4: Different sags fluctuations

For the 3 sag differences that the tool will see during its trajectory above the component, we find the same range of sag fluctuations, the local fluctuation being an average value.

5. PROPOSED CRITERION

Looking to the list of CCP limitations, it is clear that the diameter of the tool (or spot size diameter) is an important parameter: it settles the limit for efficiency of CCP correction.

The second important point is of course the flatness requirement for the surface.

So the main idea is to compare this flatness required to the sag fluctuation under the tool. Three sags fluctuations are defined here over. The most critical is the local fluctuation because the meridian fluctuation (from centre to the edge of the component) can be compensated by the trajectory calculation. The local fluctuation cannot be compensated and is equivalent to a change of tool removal function according to tool position.

Even more for direct off-axis surface, the local fluctuation will be more appropriate for comparison than difference between the edge and the centre, which does not exist!

So comparing this 2 values for the main critical point which is the edge of the component ($r = \phi/2$), we obtain:

$$F = \frac{-Cc \times T^2 \times \phi^2}{4 \times (4 \times R^2 - Cc \times \phi^2)^{1.5}}$$

With F flatness of surface (we use rms value), and ϕ diameter of the total aspherical component (if it is a direct off-axis surface, ϕ will be the diameter of the equivalent on-axis surface called the parent surface).

Calculating the diameter of the tool, we obtain:

$$T = \frac{2}{\phi} \times \sqrt{\frac{F}{|Cc|}} \times (4 \times R^2 - Cc \times \phi^2)^{0.75}$$

This diameter is the criterion of aspherical manufacturing difficulty:

$$\text{Criterion} = \frac{2}{\phi} \times \sqrt{\frac{F}{|Cc|}} \times (4 \times R^2 - Cc \times \phi^2)^{0.75}$$

According to this criterion, a smaller value means a surface more complex to manufacture because:

- It increases time and therefore probability of problems linked to removal function stability of the tool. It will create high frequency defect (that will limits the performances obtained on the surface) and low frequency defect that will request complementary runs,
- It increases the risk of indirect errors linked to misalignments on small tool.

6. EXPERIMENTS OF THE CRITERION

Following figure 5 gives examples of surfaces manufactured in the past by SESO:

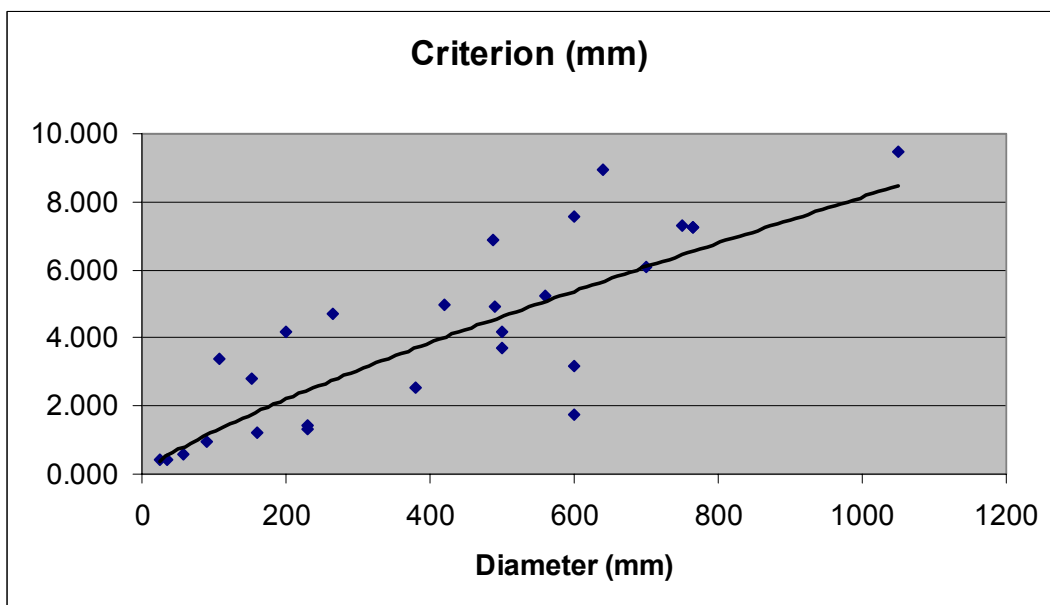


Figure 5: Criterion for many manufactured surfaces

This figure includes many direct off-axis mirrors, which were finished on our mechanical CCP. The diameter used in this table is the real diameter of the component manufactured (on the opposite, the diameter for the criterion formula is the total diameter of the equivalent parent surface). It includes also mirrors manufactured with a QED CCP.

Looking the graph we find also a regular fluctuation in aspherical surface criterion versus diameter. It is a result of the fact that for small diameter, it is logic to use small tool. This correlation confirms the criterion quality.

Finishing of aspherical surface with low rms value (better than $\lambda/60$ rms on surface, so wave-front error (wfe) better than $\lambda/30$ rms) is possible with our equipments. In the following example, we see some high frequency residual defects and also some artefacts (local circular forms), which were due to interferences in the control set-up and did not exist on the surface. Surface map (figure 6) of aspherical surface diameter 600 mm ($\lambda/66$ rms) obtained is:

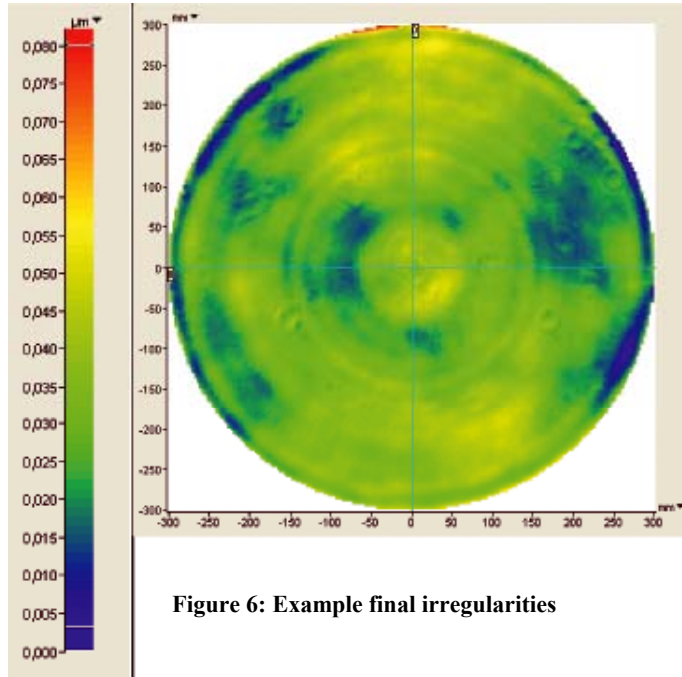


Figure 6: Example final irregularities

The next example (figure 7) is an off-axis mirror with wfe $\lambda/35$ rms. It has a criterion of 1.31 mm and it is issued from a parent mirror F/1 with a criterion of 1.76 mm:

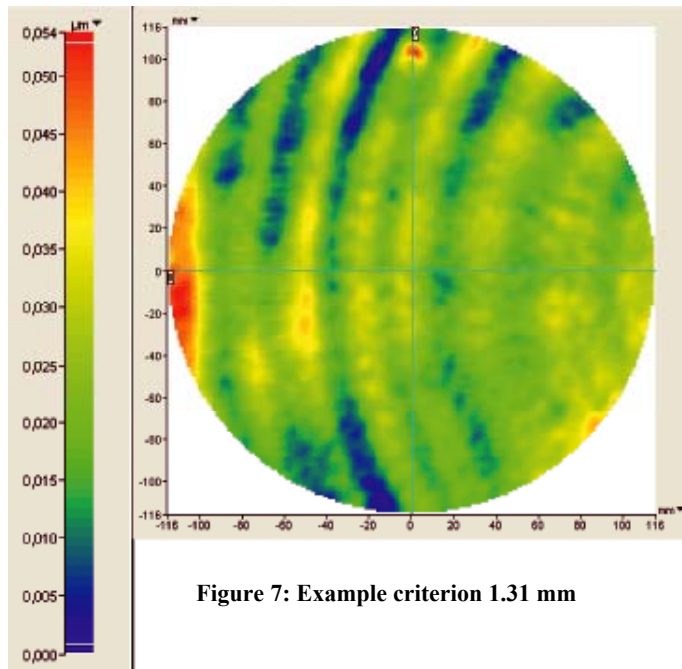


Figure 7: Example criterion 1.31 mm

Other example (figure 8) is a direct off-axis mirror diameter 560 mm wfe $\lambda/16$ rms with off-axis of 1362 mm and criterion of 5.2 mm:

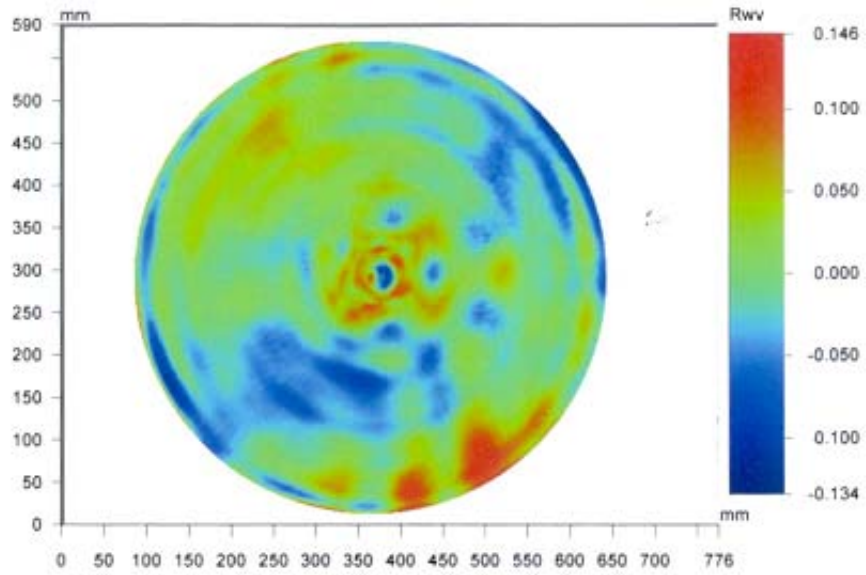


Figure 8: Example of direct off-axis finishing

7. ADVANTAGES OF THIS CRITERION FOR OFF-AXIS SURFACES

If we calculate the Mercier's Criterion for same surfaces as figure n°5, we find the following figure 9:

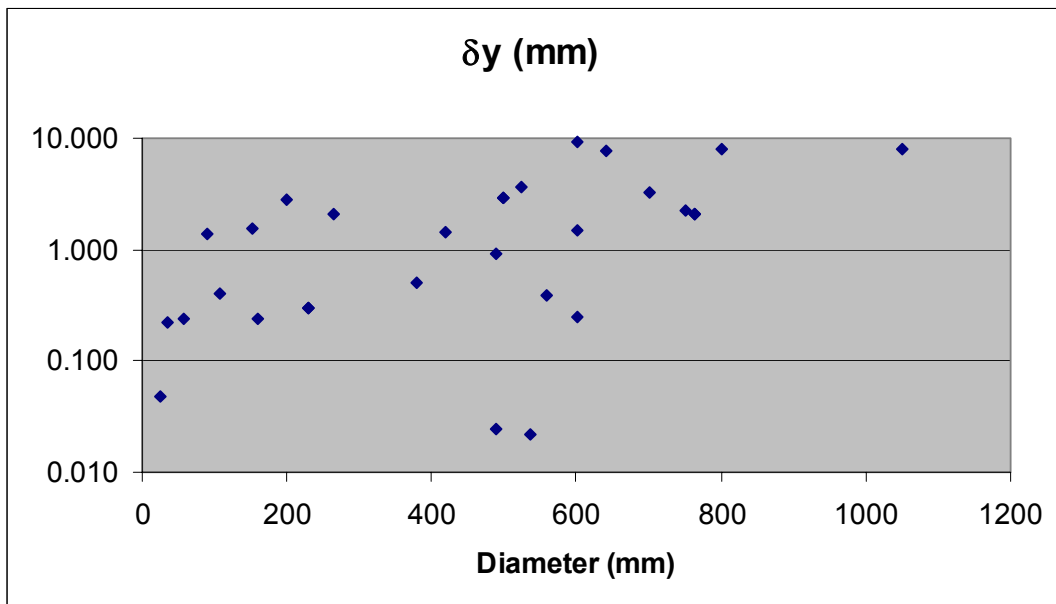


Figure 9: Mercier's criterion for many manufactured surfaces

As seen on this figure 9, it is necessary to use a log scale to see a similar dispersion of the values. Also many surfaces are with very low Mercier's criterion value (less than 0.1 mm) that was considered like non feasible. These low points are mainly direct off-axis surfaces.

In the concept, our criterion is similar as Mercier's criterion in the fact that the deviation to the sphere is compared to a specific flatness requirement. The advantage of our criterion is to be more adapted to new technologies meaning small tool and it includes the real requirement of flatness and not a standard value.

Concerning the representativity of the criterion versus manufacturing processes, we can say that criterion is adapted for all equipments as the sag fluctuations under the tool creates non uniform removal law under the tool. It is representative as well for CNC grinding used for aspherization as for CCPs used for finishing. The removal law changes according to position of the tool versus the surface.

In each case, the minimum value of criterion acceptable for design and manufacturing will be defined according to capabilities of the CCP equipment (total diameter of component, tool diameters available, reasonable removal rate according to production time).

8. CONCLUSION

The criterion defined for aspherical manufacturing that we used since many years to design (for example on space program) and to production, is adapted for current technologies. It could be very useful for all optical designers to optimise surfaces definition according to production capabilities. This criterion also can help manufacturing engineers to define tests for theirs CCP equipments and therefore to improve it. Now we suggest to increase the number of data concerning aspherical surfaces manufactured in other companies in order to confirm the quality of the criterion. In the future, it will be very interesting to define a complementary criterion for the control of the surface, because on aspherical surface and even more for off-axis surface the control set-up is a part of performance limitation.

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