

A Rigorous Nomenclature for Three-Mirror Anastigmat Systems: Classification and Applications

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ABSTRACT

Unobscured reflective optical systems (e.g., TMAs, 4MAs) are widely used in space, but their classification is still difficult because there is no standardized nomenclature. With reflective freeform optics enabling far more diverse geometries, generic labels like “TMA” or designer names alone are no longer sufficient to accurately describe and compare design families. This paper introduces a rigorous, additive naming scheme for multi-mirror anastigmatic systems. The on-axis designation encodes, via letters and numbers, the presence of intermediate images and the concavity/convexity of mirrors, yielding mathematically unique family identifiers. An extended off-axis notation additionally specifies reflection topology (crossing or non-crossing), orientation, and which beam portions intersect, allowing complete identification of the possible skeletons for TMAs and 4MAs within the established scope. The approach is validated by an on-axis study that refines classical F#/FOV maps into a Smith-chart-like view, and by off-axis representation of skeleton families. Overall, the nomenclature improves communication, understanding of optical behaviors, and supports efficient exploration and classification of unobscured multi-mirror reflective systems.

Keywords: Optical design, classification, reflective optics, nomenclature , TMA

1. INTRODUCTION

In the field of space optics, the use of "unobscured aperture systems" is often mandatory due to the large diameters of optics, issues with stray light, or broad spectral bands that are difficult to achromatize. These systems include TMAs (Three-Mirror Anastigmat), 4MAs (Four-Mirror Anastigmat), 5MAs, and all non-rotationally symmetric reflective optical systems.

The first TMA was proposed in 1935 by Maurice PAUL (Ref [1]), followed by other solutions in the 1960s and 1970s, before being formalized and generalized by D. Korsch in the 1970s (Ref [2]), based on former work on aberration correction by K. Schwarzschild (Ref [3]). These optical systems have thus become standard optics used almost systematically in the space domain. However, although different types of TMAs exist with completely different properties, most often all these optics are simply referred to as "TMA" without specifying which TMA family they belong to. Sometimes, certain publications try to clarify the family, most often by specifying the name of the first optical designer who proposed or patented the design: for example, one speaks of TMA of the "Korsch" type, "Cook" type, "Paul-Baker," etc. Occasionally, articles refer to famous designs, and one might read "James Webb-like TMA," and so forth. However, there is no standardized and clear nomenclature to navigate the entire range of TMAs. This is even more true for 4MAs, 5MAs, and so on. Table 1 illustrates a partial list of some TMA designs and some nomenclature found in literature.¹

Need for on-axis classification

As the naturalist Linnaeus said, “Objects are distinguished and known by classifying them methodically and giving them appropriate names. Therefore, classification and name-giving will be the foundation of our science”. Linnaeus believed that classification and nomenclature were fundamental tools to make nature understandable. Naming a plant or an animal gives it a place within an ordered system, which allows studying its relationships with other organisms and better understanding its characteristics. It is with this goal in mind that we have developed our nomenclature for TMAs, 4MAs, and so forth along the axis.

Need for off-axis classification

Over the past ten years, the issue has become even more complex with the emergence of Freeform mirrors. Indeed, in order to "unobscure" reflective anastigmat systems, classical solutions using aspheric mirrors only play with the field off-axis and/or the pupil off-axis, which leaves little choice in the shape of TMAs. The advent of Freeform mirrors now also allows mirrors to be tilted. It thus becomes possible to explore different geometries for the same on-axis TMA. This was explored by A. Bauer (Ref [9]) using the NAT method (Ref [8]), and he showed that not all configurations are equivalent in terms of image quality and optical properties. An initial taxonomy was proposed in the article (geometries A, B, C, ...), but this taxonomy is incomplete (it does not cover all possible combinations with a TMA) and without a model or exact knowledge of the name of each geometry, it is impossible to represent it. In Ref[10], an exploration method for FF TMA is described. For coaxial configurations, a nomenclature based on the presence (P) or absence (N) of an intermediate image is used. For off-axis configurations, the authors aimed to present all possible unfolded configurations as starting points for gradient descent. However, they did not provide a naming scheme for these configurations, which consequently led to the omission of two classes. Let us also mention [11] for the two-mirror case, in which the authors begin to assign intelligible names to the configurations—such as the ‘4’ and the ‘Z’ configurations—but once again omit one equivalent class. The work of [12] is also related to the present study, as it investigates the different families corresponding to the connected components of the definition domain of an optical quality-based merit function for planar symmetric, distortion-free and obscuration-free configurations. However, the obtained configurations are not given intelligible names, but rather are simply labeled A, B, C, ..., G.

The absolute need for nomenclature becomes glaringly apparent when reading the article by B. Zhang (Ref [13]). In this article, millions of TMA designs were automatically generated using HPC approach, but without a robust and intuitive nomenclature, it is practically impossible to navigate the “jungle” of all these TMAs.

Contribution

In this article we present an on-axis nomenclature on axis which is mathematically rigorous and furthermore enables one to visualize the shape of the TMA, 4MA, etc., simply by reading its designation, without requiring prior knowledge of each nomenclature.

In Section 3, we will refine our nomenclature which allows the geometry of the optical system to be drawn directly by reading the name, and mathematically covering all cases for a TMA and 4MA. The nomenclature on the geometry or “skeleton” is compatible with and complementary to the nomenclature on the axis.

In the final section we will illustrate the pertinence of our nomenclature by studying in details the case of $N=3$ mirrors; identifying families using our method as a compass, we were able to draw a map, in the spirit of the well-known Smith refractive design chart (Ref[5]), describing the best TMA designs in terms of image quality and compactness, as a function of field of view and F-number. To the best of authors knowledge, it is the first time that such a chart is drawn.

We will also illustrate the usefulness of the off-axis nomenclature, enabling the exploration and classification of the different possible skeletons for the same TMA solution.

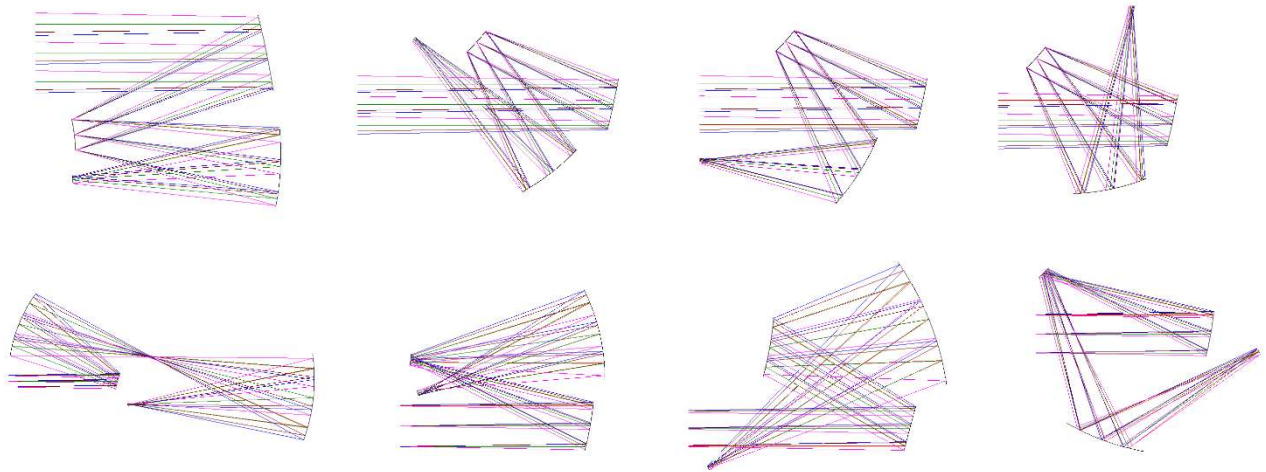


Figure 1. Examples of different families of TMA and different “skeletons”. How to differentiate all this designs ? All these designs are currently name ‘TMA’ however each of them has its own characteristics and shall be named by its own name

2. ON-AXIS CLASSIFICATION

The proposed nomenclature is composed of letters (P and N) and numbers (0 and 1).

The letters P and N relate to the sign of the ray-height ratios after each mirror, more specifically to the presence or absence of an intermediate image between the mirrors. The numbers correspond to the concave or convex shape of the mirrors.

The name of the TMA, 4MA, ... N-MA is constructed additively: the first letter corresponds to mirror M_1 — whether the mirror’s magnification is Positive (without an intermediate image) or Negative (with an intermediate image); the second letter corresponds to mirror M_2 , and so on up to mirror M_{N-1} . The use of the letters P and N comes from the articles by D. Korsch.

Next, the numbers correspond to the shape of the mirror: ‘1’ = concave, ‘0’ = convex. Here again, the name is written additively: the 1st number corresponds to M_1 , the 2nd to M_2 , and the N-th to the mirror M_N .

In Ref [6] it has been showed that this classification is mathematically certified, meaning, among other properties, that two different systems will bear two different names, and that every system has a name, that is unique.

Figure 2 illustrates the nomenclature for a Korsch-type TMA or ‘PN101’.

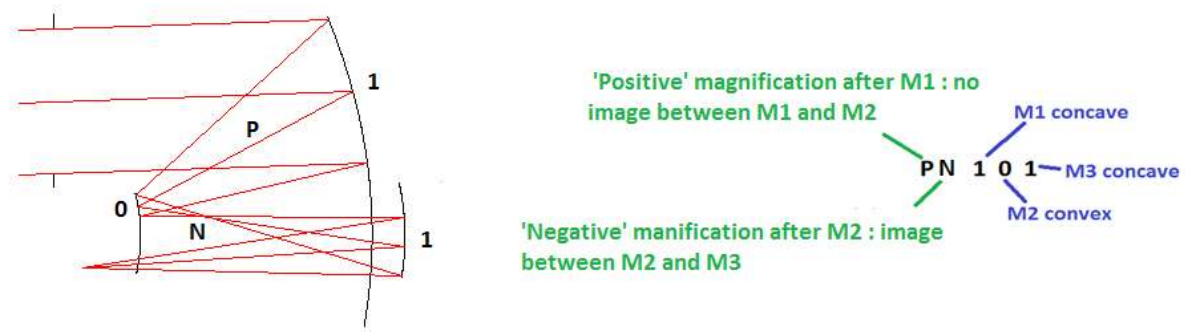
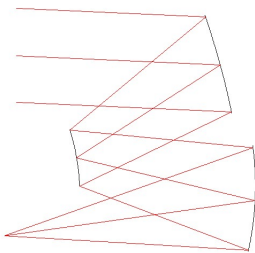
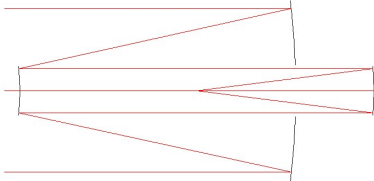
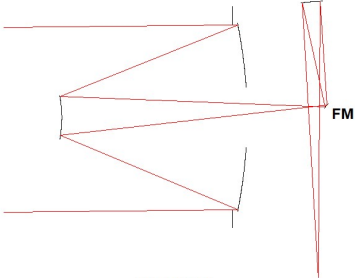
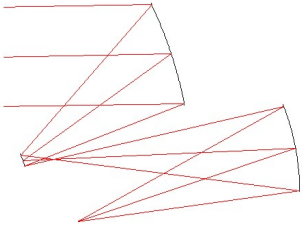
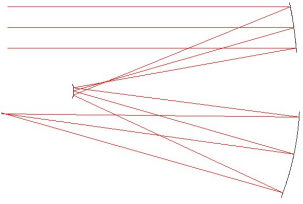
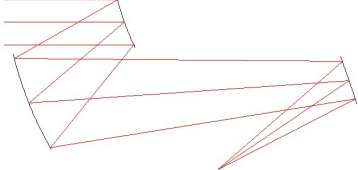


Figure 2. Illustration of the name of the TMA in the PN101 family. There is no intermediate image between M_1 and M_2 , so the magnification M_1 is positive. Then, there is an intermediate image between M_2 and M_3 , so the magnification M_2 is negative. M_1 is concave (1), M_2 is convex (0), and M_3 is concave (1): P-N-1-0-1. The system can be drawn by reading its name; there is no need to memorize a classification.

The proposed nomenclature is not based on an arbitrary classification relying on a table associating a name with a family of designs (e.g., TMA 'Type I' = Korsch TMA; TMA 'Type II' = Cook TMA; etc.), but rather on a nomenclature method that allows one to almost instantly sketch the optical layout simply by reading the name. For example, a Korsch TMA is a PN101, a Paul TMA is a PP101, and so forth.

Table 1. Examples of TMAs names seen in bibliography. There is no standard in the naming of TMAs.

TMA	Actual nomenclature seen in bibliography
 PP101	- Wetherill and Womble Objective "TMA" ...
 PP101	- Paul-Baker Telescope - Wiltrop Telescope ...

 PN101	• 3-mirrors Cassegrain • Korsch Telescope • James Webb like Telescope • ...
 PN101	• Cook Objective • “TMA” • ...
 NP101	• Three mirrors Korsch objective • “TMA” • Reflective Triplet • ...
 PP011	• Walruss • “TMA” • ...

3. OFF-AXIS CLASSIFICATION

Explanation

Once nomenclature of on-axis designs is done, we have to propose an off-axis nomenclature. Complete description and mathematical study of the nomenclature is proposed in Ref [6] and Ref [7], here we will explain briefly how the nomenclature works. As for the case of on-axis, the off-axis classification is mathematically certified, but only up to $N=4$ mirrors.

The nomenclature of the different off-axis skeletons is also additive, mirror by mirror. After each mirror, it is necessary to determine the type of reflection: does the reflected beam cross another beam before hitting the next mirror? If yes, we use the letter "X"; if not, we use the letter "V," which visually suggests the crossing or the direct reflection to the next mirror.

Next, the orientation of the angle between the incident and reflected beams must be specified: clockwise or anti-clockwise ("C" or "A").

Finally - only in the case of reflection with beam crossing- the crossed beams must be specified. For this, the beam portions are numbered: 0 for the incident beam, 1 for the beam after reflection on M_{i-1} , 2 for the beam after reflection on M_i , and so on.

Following figures explain this nomenclature.

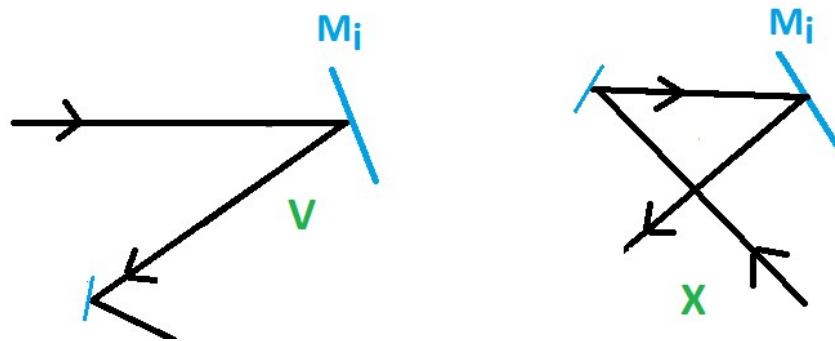


Figure 3. Two types of reflection: one reflection goes directly to the mirror M_{i+1} without crossing another optical beam : this is called a "V-type" crossing). The second type of reflection involves the light crossing another optical beam : this is called an "X-type" crossing.

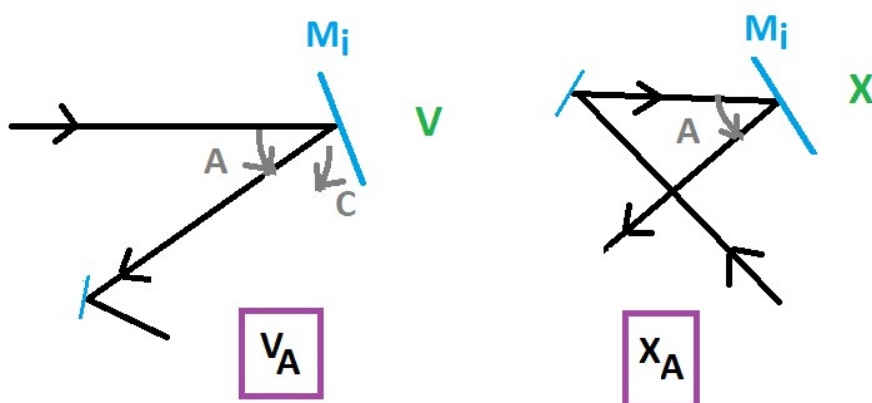


Figure 4. Once the type of crossing, X or V, has been determined, it is necessary to define the direction of orientation: either clockwise 'C' or anti-clockwise 'A'

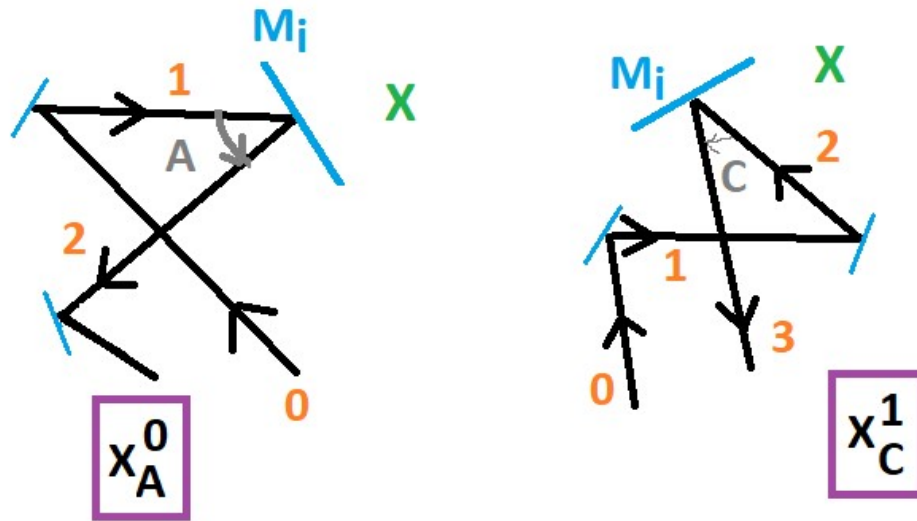


Figure 5. In the case of an X-type crossing reflection, it is necessary to specify which beam is being crossed.

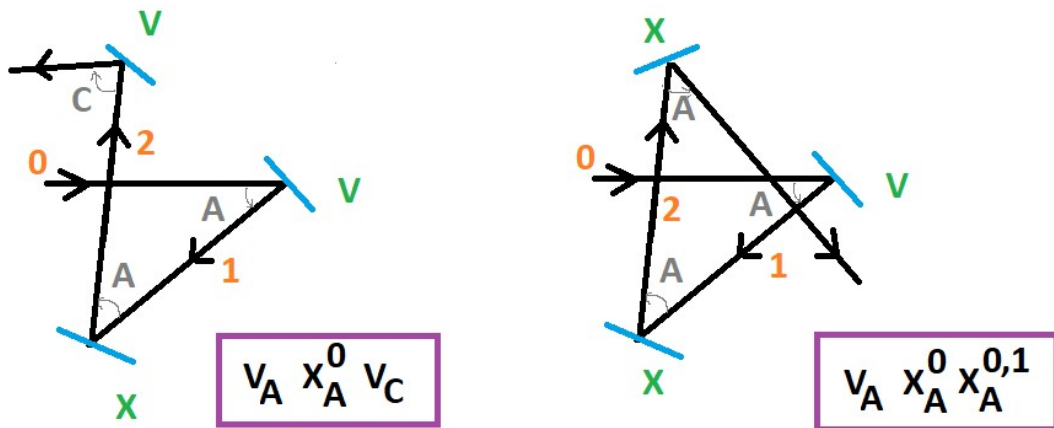


Figure 6. Two examples of skeletons and nomenclature. As with the axial nomenclature, the idea is to be able to directly draw the optical design simply by reading the name.

Final result

This mathematical approach has allowed us to identify all possible skeletons for the TMA (16 possibilities, see Figure 7) and for the 4MA (144 possibilities). The proposed nomenclature now enables us to meet our initial requirement: to give a unique name to each TMA and 4MA, and for each geometric configuration or skeleton. The TMAs in Figure 1 can now be assigned a unique name (see Figure 8).

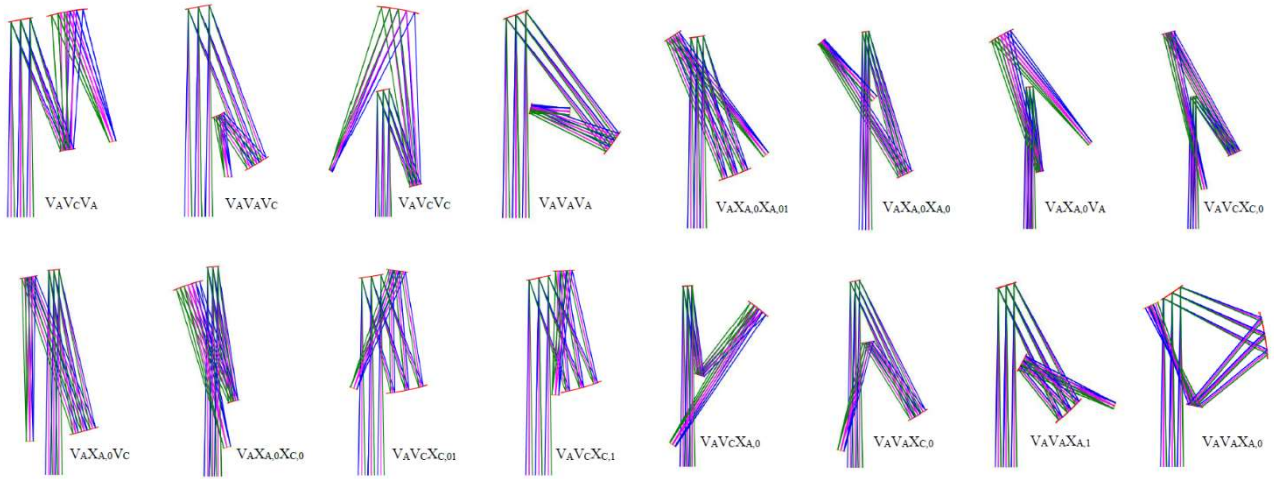


Figure 7. There are exactly 16 classes of skeletons for a TMA, and exactly 144 for a 4MA (Ref [7]).

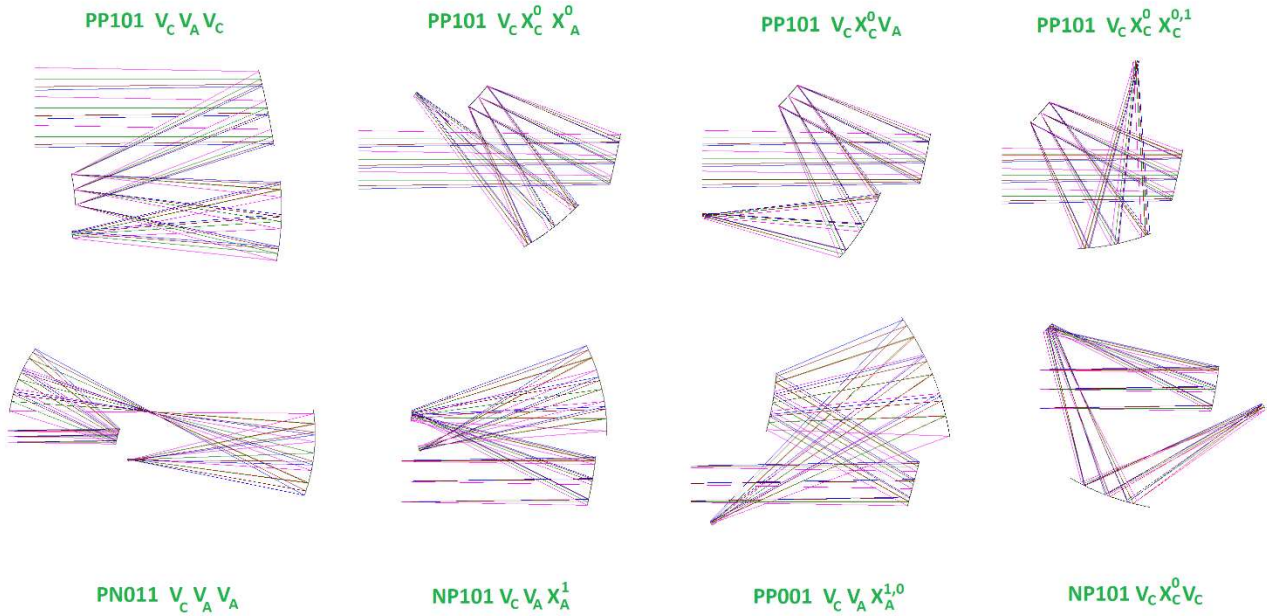


Figure 8. Examples of different families of TMA and different “skeletons”. Our nomenclature enables to give a unique name to each type of TMA and each “skeletons”. This additive nomenclature enable to directly draw the optical design, just by reading is name, or to find easily the name of the TMA,4MA,..just by observing its drawing.

4. USE OF THE NOMENCLATURE TO STUDY TMAs ON AXIS : CLASSICAL F#/FOV MAP COMPLETED WITH TMA FAMILIES

Real interest of the nomenclature in TMAs exploration

We are now well-equipped to explore and navigate the jungle of TMAs, 4MAs, and so on. We illustrate in detail the value of our nomenclature for the study of TMAs on axis in Ref [14].

There are only 10 possible families of TMAs (without field curvature). A pioneer in the study of TMAs, such as Dietrich Korsch, identified these 10 types of TMAs and grouped them into 3 subgroups, based on the presence or absence of an intermediate image and on the sign of the image size ratios. Our nomenclature clearly indicates in which subgroup each type of TMA (P/N) appears, by adding the shape of the mirrors (0/1).

Each family of TMA has its own specific characteristics and qualities.

Detailed performance of each TMA family

To study the characteristics of each family, we have analyzed hundreds of thousands of TMAs to answer the following question: for which range of $f\#$ and FOV is each TMA family usable, and with what minimal volume?

With a fixed focal length, for each square $\text{FOV}/f\#$ pair, we determine whether there exists a solution with good image quality (average WFE in the field < 10 nm RMS) and what its minimal volume is (normalized between 100 and 10,000). Each TMA is composed of freeform mirrors. See for detailed explanation Ref [6].

Example : PP101

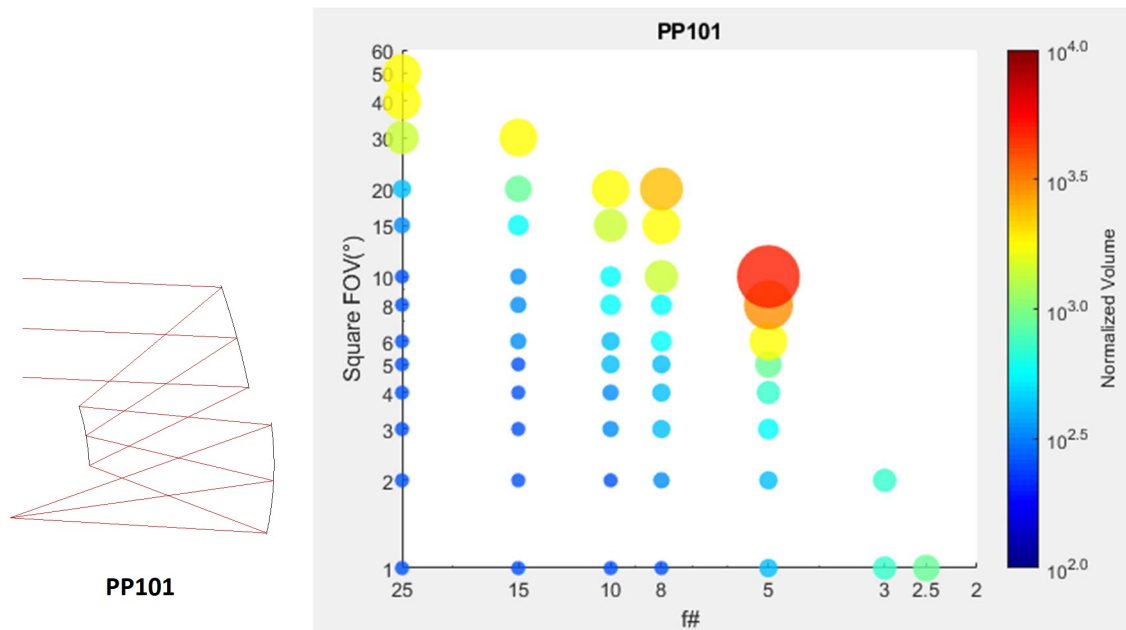


Figure 9. With a fixed focal length, for each FOV/ $f\#$ pair, we assess whether a solution exists with good image quality (average WFE in the field < 10 nm RMS) and what its minimal volume is (normalized between 100 and 10,000). Size and color of each point is proportional to the minimal volume of the TMA.

PP101 is a classical TMA, graphic shows us that it is quit compact over a large range of slow optics ($f\# < 5$) and for relatively large FOV ($< 20^\circ$)

It is now possible, based on the characteristics of each TMA family, to estimate, for each FOV/f# pair, which TMA family provides the most compact design.

We obtain 5 families out of the 10 possible, each with its own area of excellence.

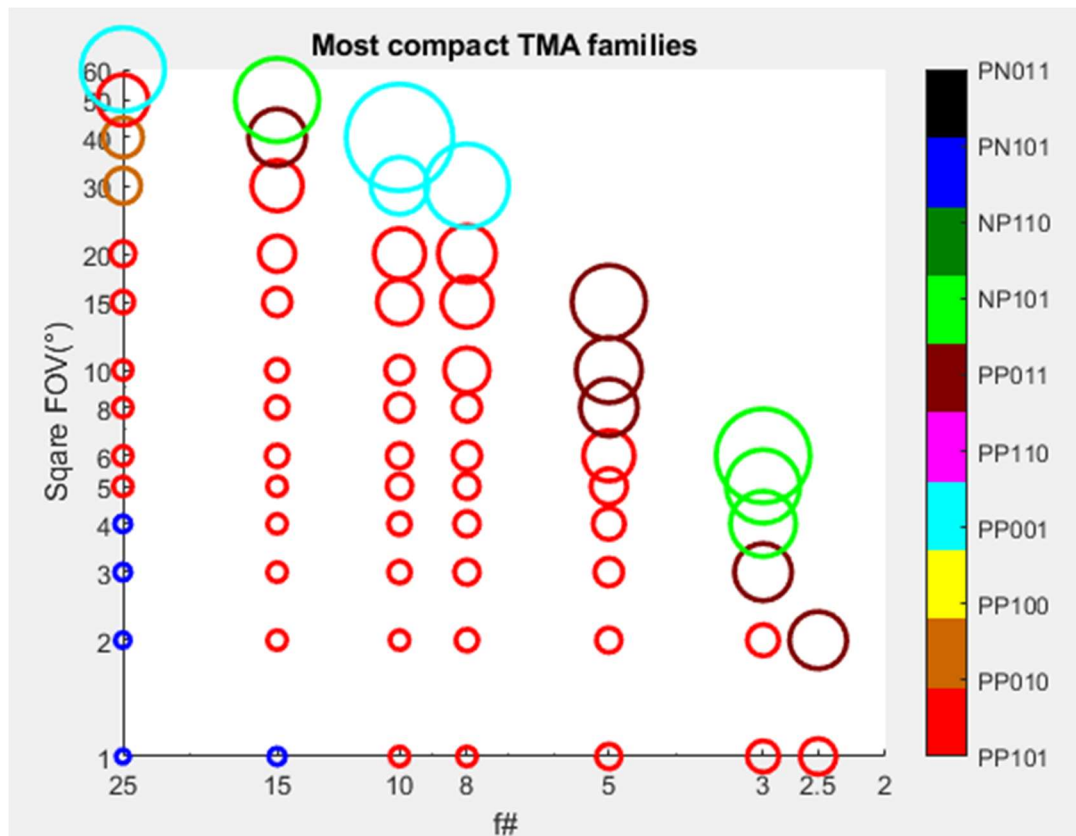


Figure 10. With a fixed focal length, for each square_FOV/f# pair, it is possible to determine the best TMA family to use in order to be both compact and efficient. It can be observed that PN101, PP101, PP010, PP011, and NP101 each have their own preferred domain. Circle's diameter is proportional to the volume of the TMA

Classical F#/FOV MAP completed with TMA families

Optical designers are familiar with the use of diagrams such as the one proposed by Warren J. Smith (Ref [5], Figure 11), showing the optical design types that are commonly used for various combinations of aperture and field of view. We can also observe that TMAs are represented on the diagram under the name "unobscured 3 mirrors."

First, let's note that the use of freeform mirrors allows us to greatly extend the area proposed by J. Smith. Moreover, thanks to our nomenclature, it is now possible to specify, within the domain of "unobscured 3 mirrors," what the preferred area is for each TMA family.

Second, in Figure 22, as with the classic Warren J. Smith diagram, each area has more or less diffused and overlapping boundaries. Specific constraints such as pupil position, distortion, etc., may influence the choice of different TMAs.

However, this diagram has the major advantage of clarifying the preferred domains of use for each family, and it highlights the fact that each TMA deserves its own name!

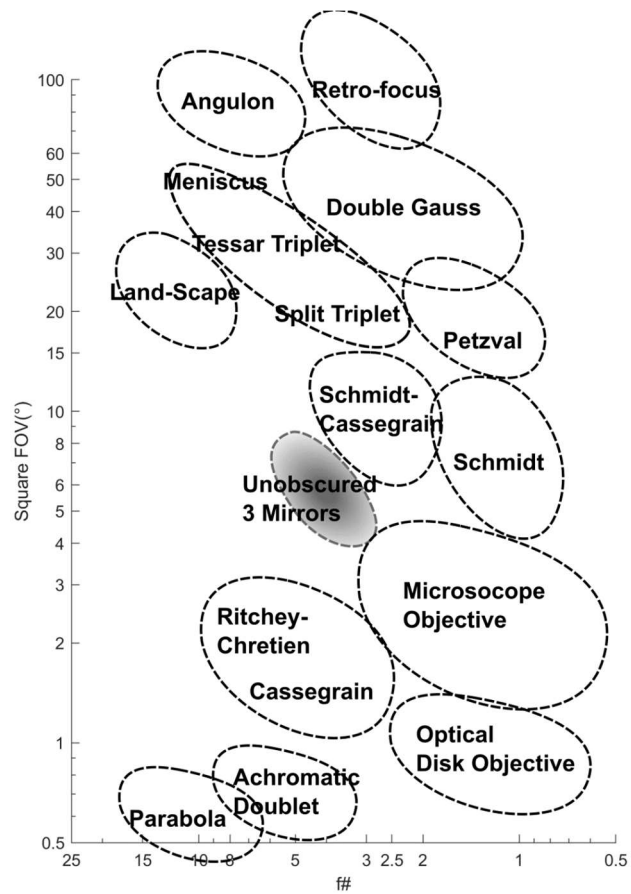


Figure 11. Classical map of optical design types which are commonly used for various combination of aperture and field of view.

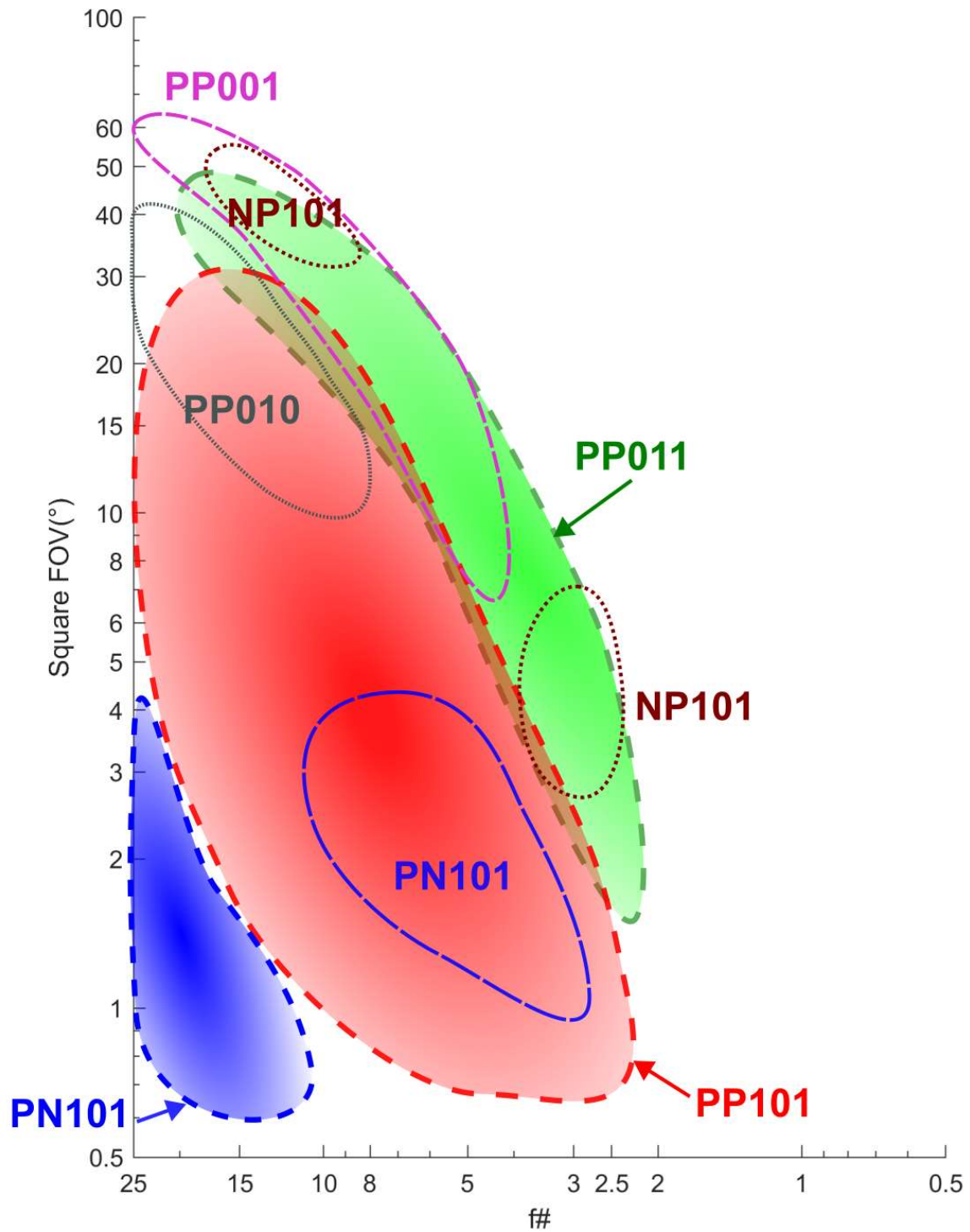


Figure 12. As in the standard chart, we have represented the areas of interest for the different TMA families according to the FOV- $f\#$ combination. For each combination, the family of TMA offering the most compact design (with good image quality) is indicated. The families represented by colored areas (PN101, PP101, PP011) are the most compact TMA families. In certain areas, other families are also compact and are interesting alternatives; these are represented by areas outlined with dashed lines.

5. USE OF THE NOMENCLATURE TO STUDY TMAS OFF AXIS

Real interest of the nomenclature in skeletons exploration

To illustrate the usefulness of off-axis nomenclature, we will study a PP101-type TMA, open to $f/3.5$ and with a field of $8^\circ \times 4^\circ$.

We have automatically explored the different skeletons that make it possible to unobscure the defined on-axis TMA. The field off-axis, the pupil off-axis, and the mirror tilts M1, M2, and M3 are explored, respectively, over the ranges $[-5^\circ$ to $-20^\circ]$, $[-100$ mm to 400 mm], and $[-25^\circ$ to $25^\circ]$. All the TMA configurations include 3 FF mirrors.

We only keep the non-vignetted TMAs and those with a WFE RMS lower than 1000 nm RMS.

Five skeleton families are represented (Figure 14) out of the 16 possible ones. Since the field of view and the aperture are quite large, it is normal not to observe all 16 skeletons. The classical skeleton of the VcVaVc type is overwhelmingly predominant, which also seems quite logical given the aperture and the field of view.

Figure 16 shows all the obtained geometries on a 3D plot, with the axes corresponding to the tilts of each of the three mirrors. However, the geometries have 5 input parameters (field off-axis, pupil off-axis, and 3 tilts). Decomposing into principal components allows all geometries to be displayed in 3D by maximizing the information shown. Figure 17 presents all geometries on the first three components (84% inertia). This is an interesting representation of the different geometries and of the overall set of possibilities covered by the five identified skeleton families.

The proposed nomenclature makes it possible to simplify the analysis and to support understanding of the phenomena involved during the various ‘desobsured’ geometries. This appears to be a very useful tool for studying TMAs.

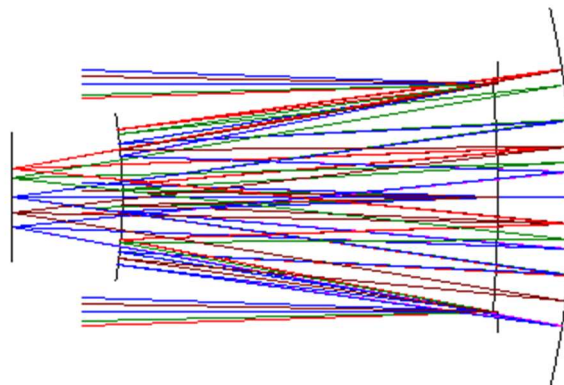


Figure 13. Design type PP101 ($f/3-4^\circ$, $8^\circ \times 4^\circ$ field), on-axis, to be “unobsured” (de-obsured) by field off-axis, pupil off-axis, and by the tilts of mirrors M1, M2, and M3.

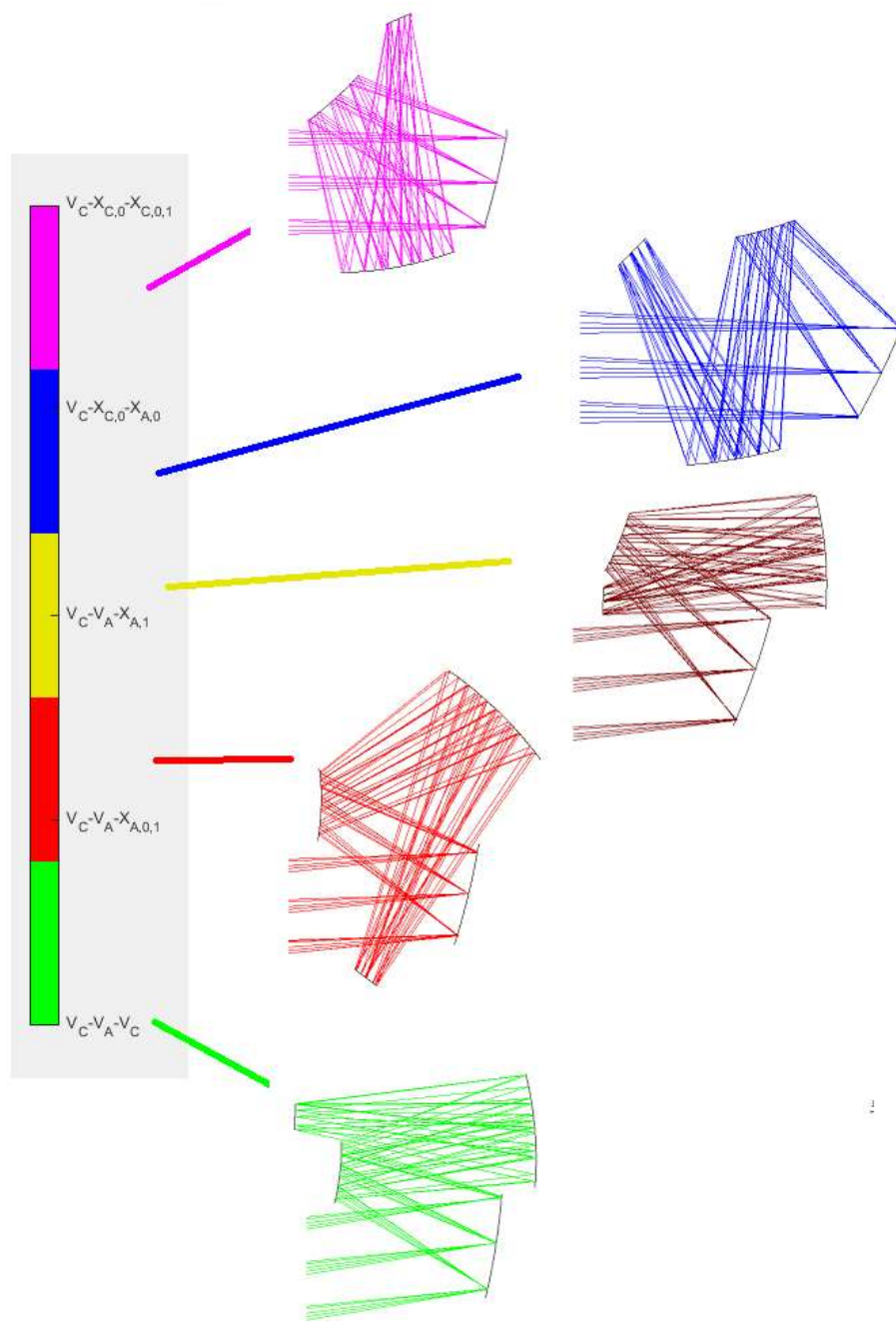


Figure 14. Details of the 5 skeleton types obtained with this PP101 (f/3-4°, 8°x4°) over more than 50,000 geometries

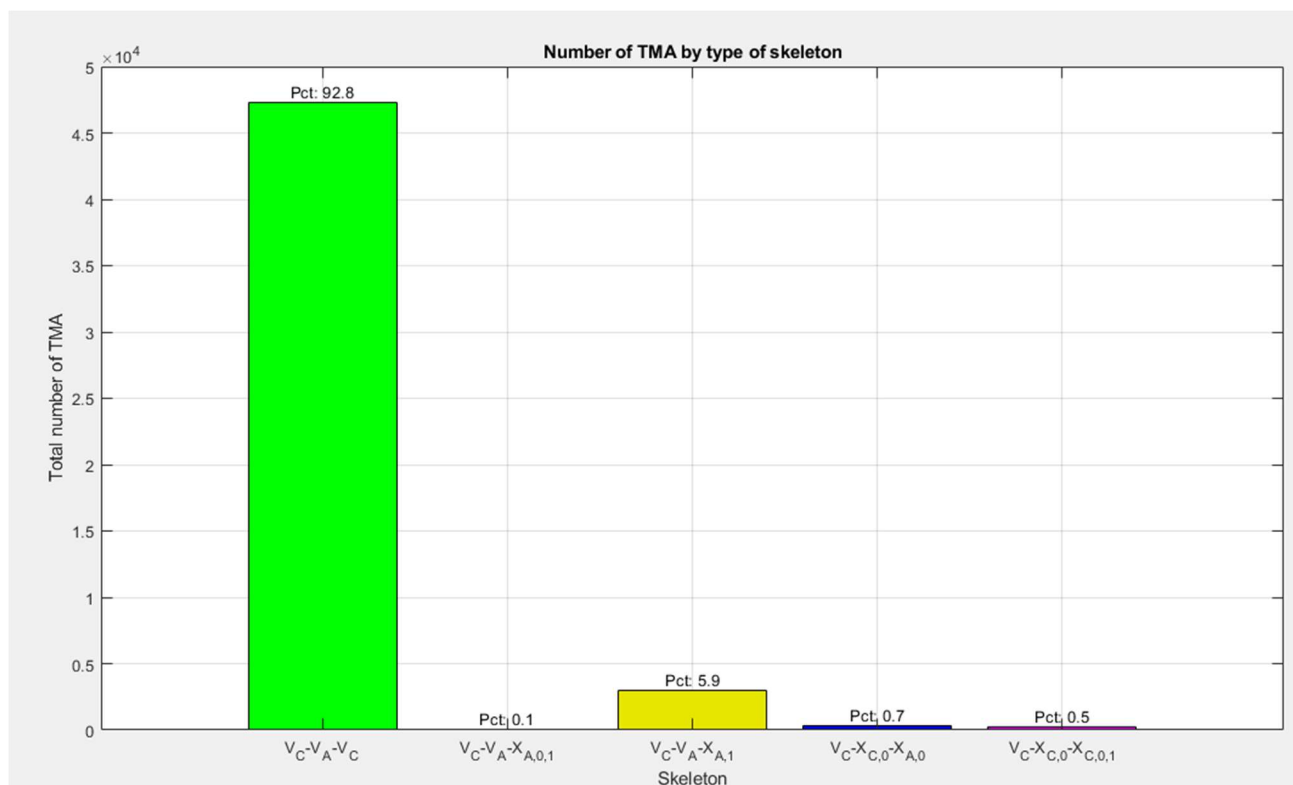


Figure 15. Distribution of the number of obtained geometries among the five skeleton families. The classical configuration VcVaVc is overwhelmingly represented in this rather open design, with a fairly large field of view.

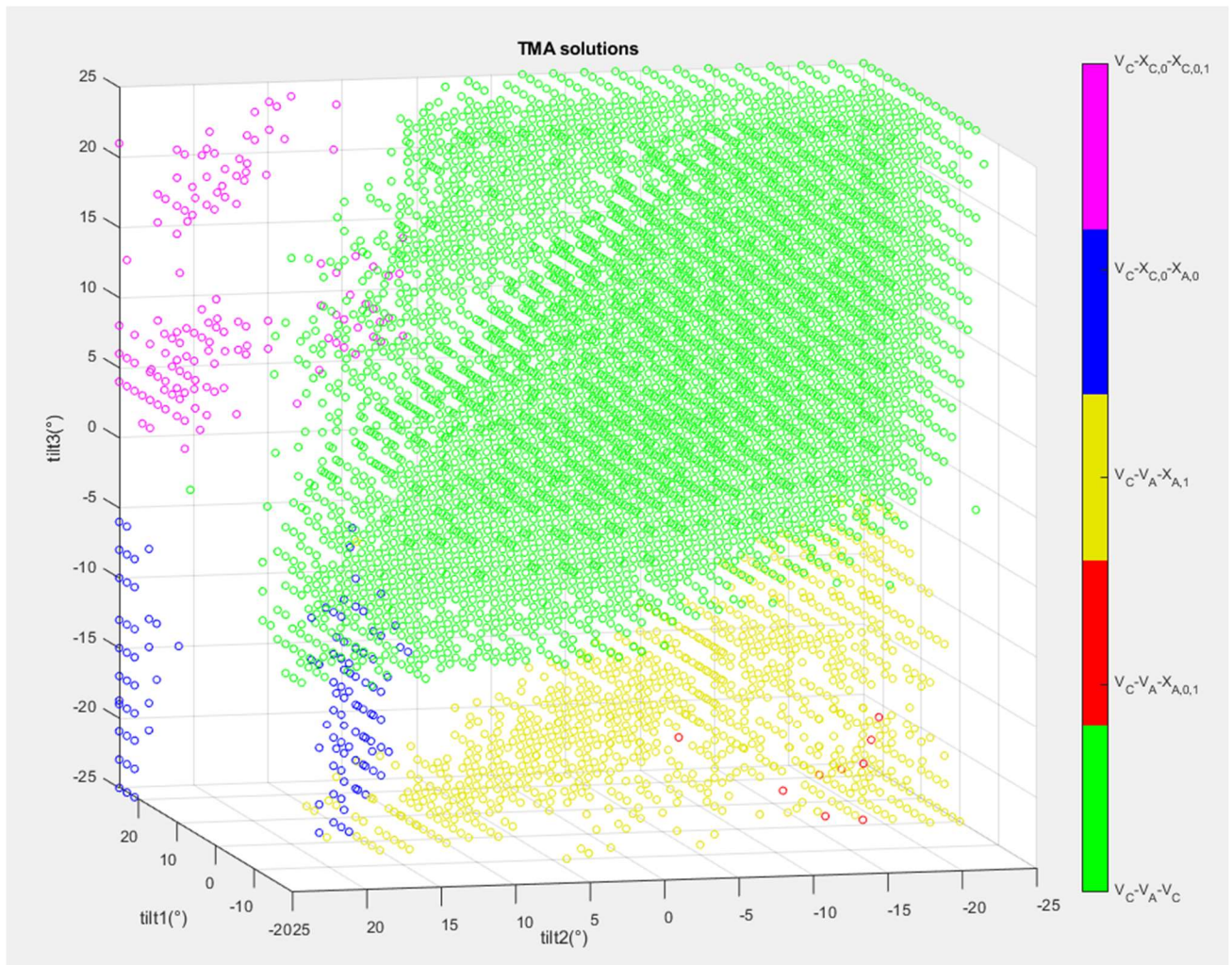


Figure 16. Example of a representation of the different geometries obtained, shown on a 3D plot as a function of the tilts of mirrors M1, M2, and M3. The empty (blank) regions correspond to angle values that do not allow light transmission without vignetting. The position and the size of the regions occupied by each skeleton are directly related to the starting TMA (mirror separations, f-number, and FOV).

Table 2. Percentage of explained inertia by each component in the principal component analysis:

CP1	: 43.89% (Cumulative : 43.89%)
CP2	: 21.17% (Cumulative: 65.06%)
CP3	: 18.00% (Cumulative : 83.06%)
CP4	: 11.35% (Cumulative : 94.41%)
CP5	: 5.59% (Cumulative: 100.00%)

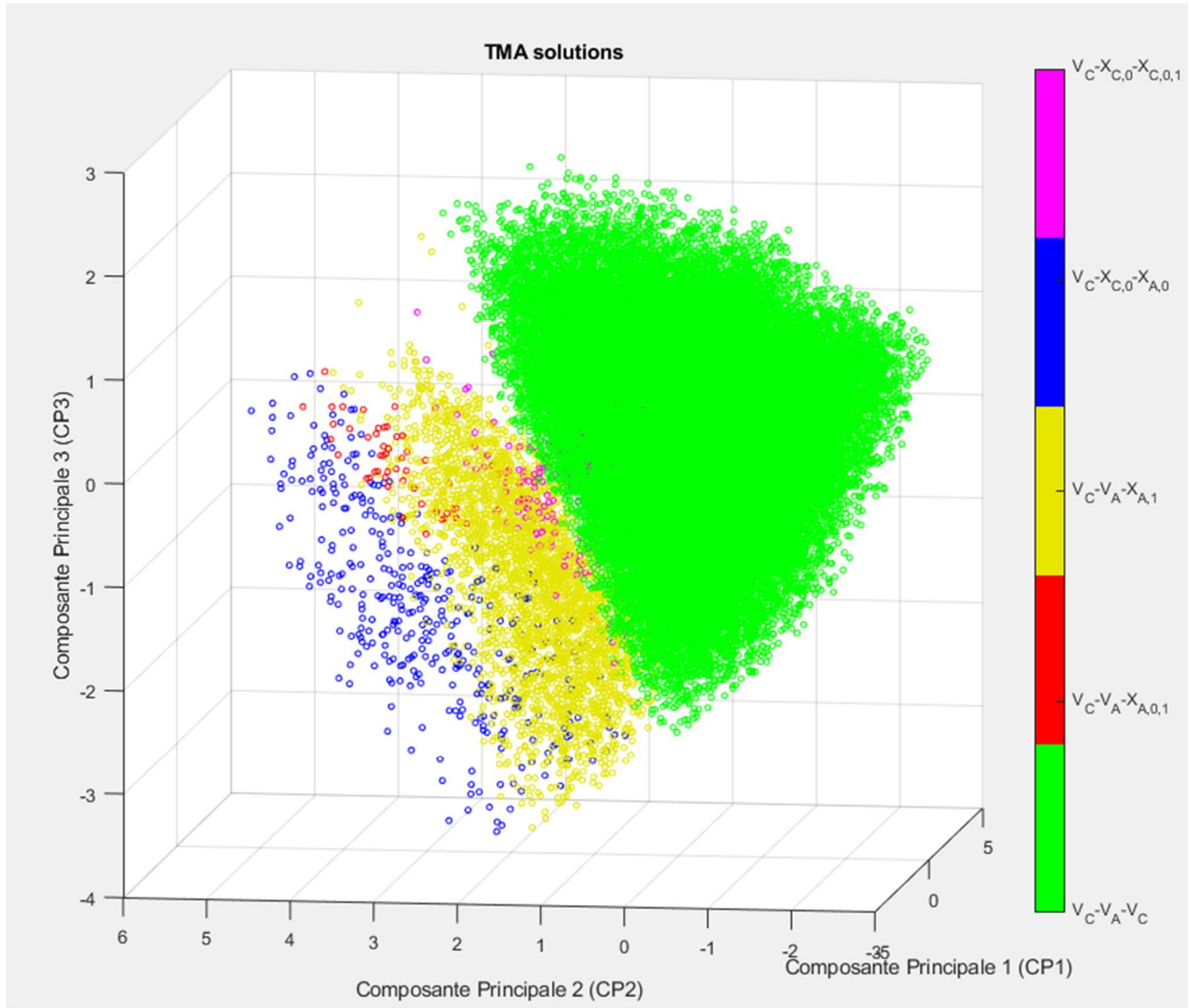


Figure 17. The 3D representation obtained using the three principal components of the PCA makes it possible to clearly separate the space occupied by the five skeleton families. The proposed nomenclature helps to simplify the analysis and to improve understanding.

6. CONCLUSION

We hope to have illustrated the imperative need to stop using the simple acronym TMA to represent the variety of different three-mirror design families, and to name each of these families. This is even more true for 4MA, 5MA, and so on.

The proposed solution does not require any reference table listing all the families and the arrangement of their “skeleton.” You simply need to read the proposed name and draw, mirror by mirror, the arrangement and position of the optical beams.

This tool seems essential for the optical designer to better understand all the available solutions, but also during discussions with other disciplines (mechanical design, integration, etc.), or during presentations to clients; the simple acronym TMA is far too limited to represent the complexity of the different families.

ACKNOWLEDGEMENTS

I thank Fanny Keller for our first discussions on this subject.
I would like to point out that ChatGPT was used to clean-up the grammar of the article.

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