Cumhuriyet Science Journal
CSJ

e-ISSN: 2587-246X
ISSN: 2587-2680

Cumhuriyet Sci. J., Vol.39-4 (2018) 1052-1062

Development of the Multi-configuration Cassegrain Collimator

Özgür SELİMOĞLU*, Mustafa EKİNCİ

TUBITAK Space Technologies Research Institute, Middle East Technical Uni. Campus, Ankara, TURKEY

Received: 17.05.2018; Accepted: 04.12.2018 *http://dx.doi.org/10.17776/csj.424574*

Abstract. A multi-configuration collimator is designed to test high precision optical instruments. Satellite imagers and solar concentrators are main candidates to be tested with this collimator. By using different measurement configurations, errors from a single test setup can be avoided. The performance of the collimator must be better than the equipment to be tested. This necessity requires the development of a highly precise instrument with a stable mechanical structure and high quality optical components. During polishing and metrology of optical mirrors, repeatability is obtained by the application of opto-mechanical principles to the mirror holders. Finite element analyses are performed to simulate gravity induced deformations, assembly tolerances and thermal variations. To understand the disturbances to the ideal WFE, variations are imported to optical software environment with the help of Zernike polynomials. In the production phase, surface qualities of the mirrors are measured by using computer generated holograms and an interferometric setup. Design, manufacturing and integration of the collimator are explained in detail.

***Keywords*:** Cassegrain collimator, multi-configuration, alignment mechanism, mirror mount design.

Çok Konfigürasyonlu Cassegrain Kolimatör Geliştirilmesi

Özet. Farklı optik ölçüm ihtiyaçlarına hizmet etmek için, birincil aynanın tüm konfigürasyonlarda sabit tutulduğu çok konfigürasyonlu bir kolimatör tasarımı kullanılması önerilmektedir. Uydu kameraları ve güneş yoğunlaştırıcıları bu kolimatör ile test edilmeye aday sistemlerdir. Kolimatör optik kalitesinin, ölçülecek cihazdan daha iyi olması gerekir. Bu gereksinim, kolimatör teleskopunun, yüksek kaliteli aynalara ve belirtilen koşullar altında çalışmasını sağlamak için kararlı bir yapıya sahip çok hassas bir cihaz olmasını zorunlu kılar. Hassasiyet gereksinimleri dikkate alındığında, parlatma ve metroloji için bağlantıların tekrarlanabilirliğini sağlamak amacıyla, ayna tutucularına opto-mekanik prensipler uygulanmaktadır. Sonlu Elemanlar Yöntemi, yer çekimi etkilerini, entegrasyon hatalarını ve sıcaklık değişimlerini simüle etmek için kullanılmıştır. Deforme olmuş optik yüzeyler için sonlu eleman analizlerinin sonuçları, tasarımı belirtilen WFE gereksinimlerine göre değerlendirmek için Zernike polinomları kullanılarak optik analiz ortamına aktarılır. Aynaların optik kalite ölçümleri, özel yapılmış CGH'ler ve interferometrik test düzenekleri kullanılarak elde edilir. Kolimatörün entegrasyonu ve hizalaması ayrıntılı olarak açıklanmıştır.

***Anahtar Kelimeler*:** Cassegrain teleskop, kolimatör, entegre opto-mekanik tasarım, esnek hizalama mekanizması.

1. INTRODUCTION

Collimator is an important optical device that is used in several optical measurement applications. By generating highly collimated light, it is possible to evaluate the performance of an optical system through measuring several important parameters such as spot diagram and field of view. Additionally, optical performance of a high resolution space-based camera needs to be evaluated in the laboratory environment before being sent to orbit. Optical tests such as star stimulus test and MTF tests need a high precision

* Corresponding author. *Email address: ozgur.selimoglu@tubitak.gov.tr*

collimator [1, 2]. Similarly, collimated light is needed for evaluation of solar concentrators where the collimation is a requirement for the evaluation of acceptance angle, concentration ratio and transmission performance [3, 4].

An on-axis, Cassegrain type collimator is developed by considering several project requirements. Collimator system can use different secondary mirrors to reach different focal lengths and collimation levels in order to fulfill different project needs. Moreover the primary mirror is designed to be a parabolic mirror and by omitting the secondary mirror, alignment errors arisen from secondary mirror placement can be avoided. Surface deformations of mirrors are calculated with FEA (Finite Element Analysis) and transformed to Zernike polynomials. Then, these polynomials are used to bring the surface deformations into the optical simulation environment and wavefront error of the collimator is obtained. A flexural alignment mechanism is designed and it is integrated to the secondary mirror in order to compensate for assembly errors and structural deformations. Mirror surfaces are polished with the help of interferometric measurements to reach a specified WFE (wavefront error). Telescope structure is integrated and alignment of the telescope is performed.

2. OPTICAL CONFIGURATIONS

Cassegrain type collimator as shown in Figure 1 is preferred to off-axis collimator types because circular symmetrical mirrors are easier to manufacture and test. Moreover the central obscuration of the collimator does not affect the optical measurements, since the space instrument to be tested with this collimator has also a central obscuration. In general, reflective collimators are preferred to the lens based refractive collimators because there is no chromatic aberration with all reflective configurations. Moreover, working wavelength interval can be adjusted by using different coating types on the mirror surfaces.

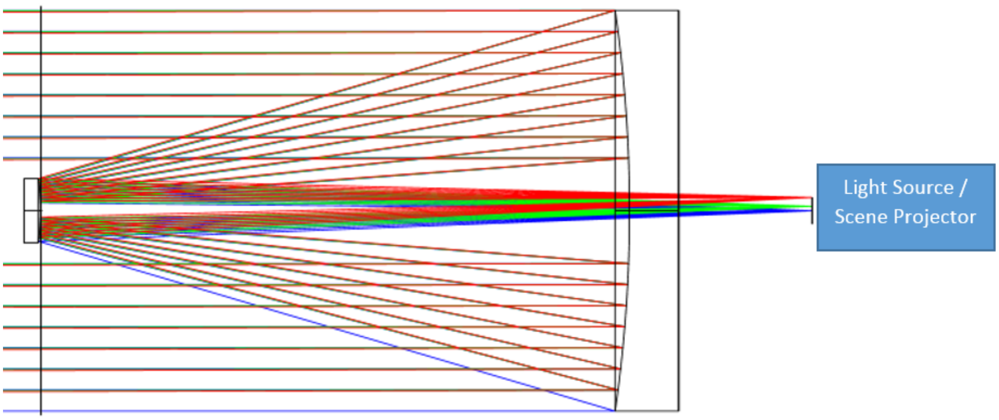


Figure 1. Cassegrain type on axis collimator design.

Computer aided techniques are used in order to evaluate different design options for collimator telescope and surface geometries are determined. Collimator telescope has two aspheric mirrors, primary mirror M1 has a conic constant of "-1", which makes it a parabolic mirror and M2 (secondary mirror) has convex hyperbolic geometry. If a point light source is positioned at the focus of the M1 mirror, collimated light can be obtained without secondary mirror. Collimator telescope is designed with surface geometry of Configuration-2 as shown in Table 1. Configuration-2 has 6200 mm focal length. By using a different secondary mirror and adjusting position of M2 with mechanical parts (Configuration-3), focal length can be elongated to reach 18000 mm as an alternative configuration. These three configurations are presented in Figure 2.

Table 1. Specifications of different configurations.

	M1 mirror	M2 mirror	M1-M2 Separation (mm)	Effective Focal length (mm)
Configuration 1 : M1 only	R: 1700 CC: -1	N/A	N/A	850
Configuration 2 : Cassegrain		R: 300.0 mm CC: -1.737	720.57	6200
Configuration 3 : Cassegrain		R:101.6 mm CC: -1.08	801.58	18000

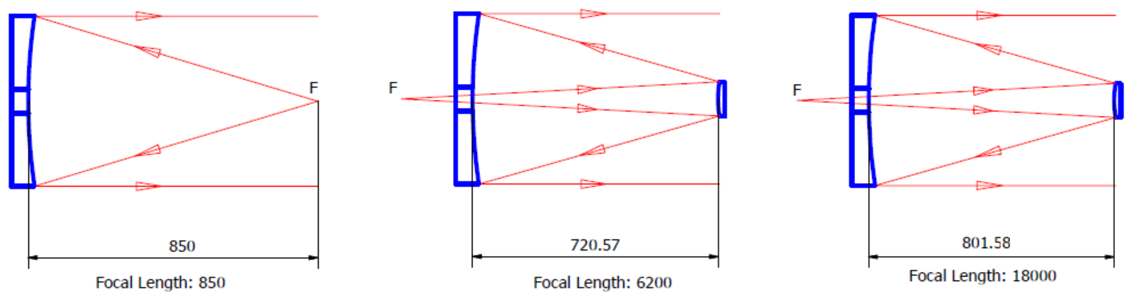


Figure 2. Collimator Configurations - Single parabolic mirror and two different Cassegrain type configurations.

Illumination leaving a point source initially reflects from the secondary mirror and becomes a collimated light after reflecting from the primary mirror. At the focus of Cassegrain telescope, fields are shown as point sources. The best performance is obtained for the central field which is on the optical axis. With respect to the distance from the optical axis, other point sources are defined at 2, 6, 7.5 millimeter. Spot diagrams show that design is diffraction limited if the source separation from the optical axis is less than 7.5 mm. The diffraction limited collimation performance for the ideal optical systems is 0.001369 mrads (Figure 3).

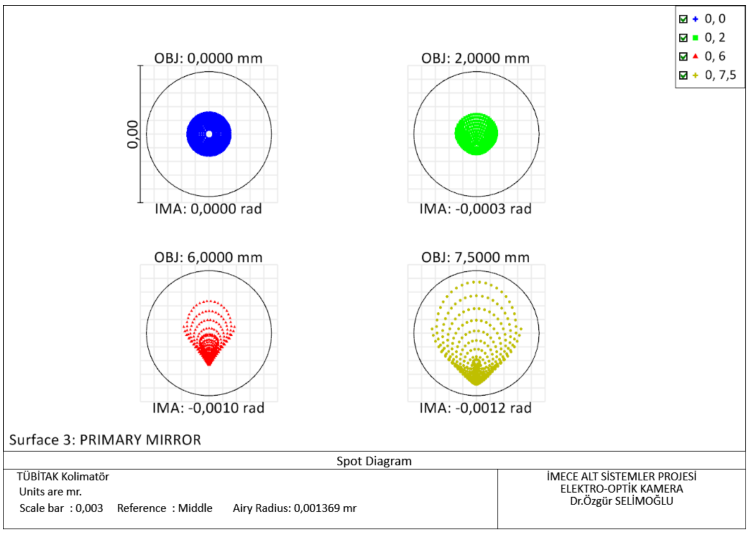


Figure 3. Collimation spot diagrams for different fields.

3. OPTO-MECHANICAL DESIGN

Cassegrain type on axis collimator incorporates two mirrors to transform point illumination to a collimated light. M1 mirror has 500 mm external diameter with 70 mm central hole while M2 mirror has 100 mm outer diameter. Both of the mirrors are made from low expansion glass ceramic (Zerodur) due to its nearly zero coefficient of thermal expansion (CTE). Mirror holders are made from invar 36 and heat treatment is applied after machining to remove any residual machining stress. M1 base plate and M2 housing are made from aluminum 7050-T7451 and six invar metering rods are connecting them together to build a stiff, light weight and thermally stable structure (Figure 4). Collimator will be used in the horizontal position and all the design and manufacturing is performed to favor optical quality at this position. To reduce the effect of thermal disturbances, the structure is constructed by combining materials with different CTE. When the temperature rises, aluminum baseplates expands more than the invar metering rods and M1-M2 separation nearly remain unchanged.

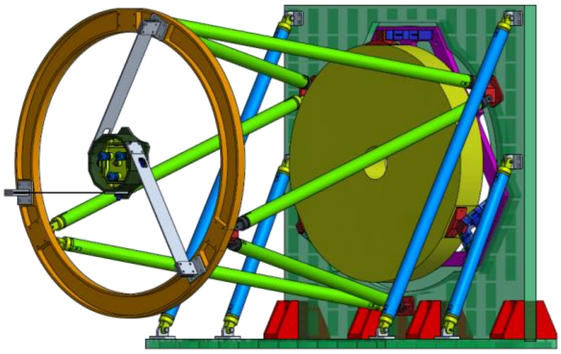


Figure 4. Cassegrain collimator mechanical assembly.

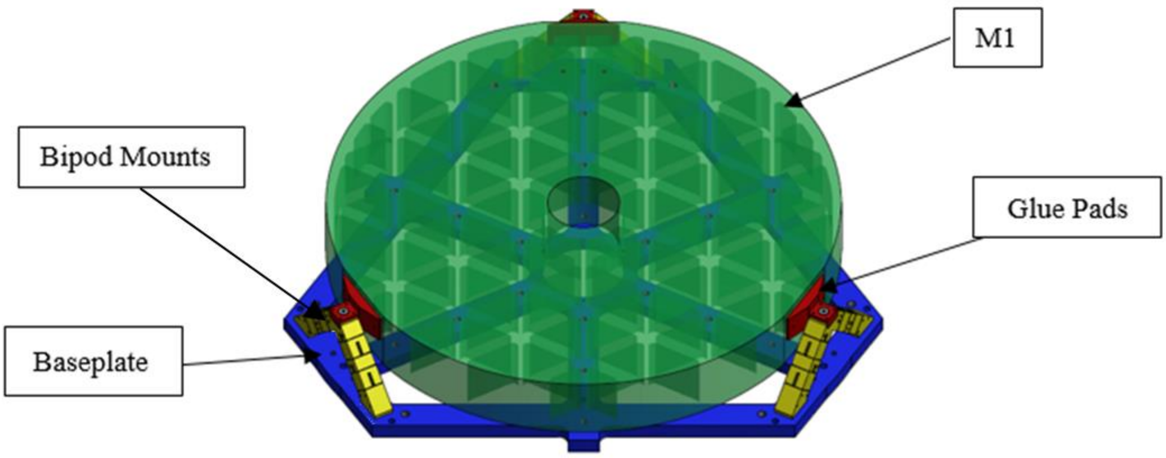


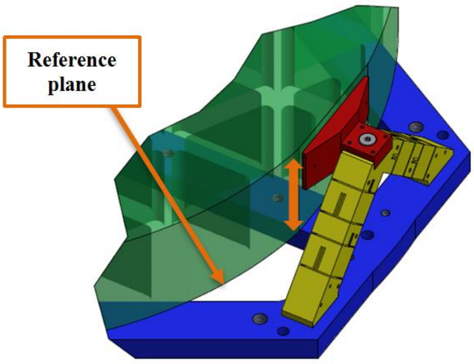
Figure 5. Primary mirror assembly with baseplate, M1 mirror, glue pads and bi-pod mounts.

M1 is machined from the back side to generate empty pockets for the mass reduction. 60% light-weighting has been applied without disturbing the stiffness of the mirror. Material removal is performed with a triangular pattern to preserve high stiffness of the mirror [5].

On the perimeter of the mirror, planar surfaces are generated with 120° separation for bonding the glue pads. This configuration ensures that at least two adhesive joints are loaded in shear for all loading cases [6]. Glue pads are the main interface between ceramic glass and metal parts. Bipod mounts and the glue pads are manufactured from Invar-36 to minimize the thermal mismatch between glass and metal parts. Glue pads have two injection holes to deliver adhesive between the glass and the glue pad at the integration phase. Pads have to be aligned at the bonding phase with the aid of holders and planar shims to keep the thickness of the adhesive at 0.1mm with a ±0.02 mm maximum deviation. 2216 B/A two part epoxy adhesive from 3M is used for bonding the glue pads to the mirror. Glue pad thickness is important at this step in order to limit the effects of shrinkage at the curing stage. Therefore volume of glue need to be minimized at the bonding stage and a room temperature curing should be performed at least for seven days without disturbing.

Flexures are holding the M1 mirror at the design position and controllably deforms under the weight of the mirror. While performing the support function, flexures should not transfer any moments or forces that can affect surface accuracy of the mirror. Three bipod flexures are used in order to isolate M1 mirror from deformations that originate from temperature fluctuations, mirror's own weight, manufacturing tolerances and integration errors. Bipod flexures are selected since they can deliver nearly ideal kinematic supporting [7]. Flexures provide separable and repeatable bolted interfaces between baseplate and glue pads which enable the mirror to be measured on the original mount between polishing iterations until WFE requirements are reached. Moreover flexures can be replaced if they are damaged during manufacturing process or as a result of aging.

Collimator overall performance is mainly depends on the quality of the primary mirror. Therefore, special consideration is necessary for the mounting of the primary mirror. Mirror mounts are designed by considering all loading cases that can be encountered within the polishing processes, construction of subassemblies, telescope final assembly and transportation. Structure of the mirror, baseplate, glue pad positions, glue pad geometries, and flexures are designed by using FEA results. To diminish bending moment on the mirror, supporting forces have to pass through its neutral plane. Any deviation from this ideal plane will influence the surface figure error of the mirror. Ideal positions of the glue pads are obtained after optimization runs within the FEA software environment. Flat back surface of the mirror is taken as the reference for the calculations. Many configurations are generated for different pad position and surface figure error of the mirror is calculated as shown in Figure 6.



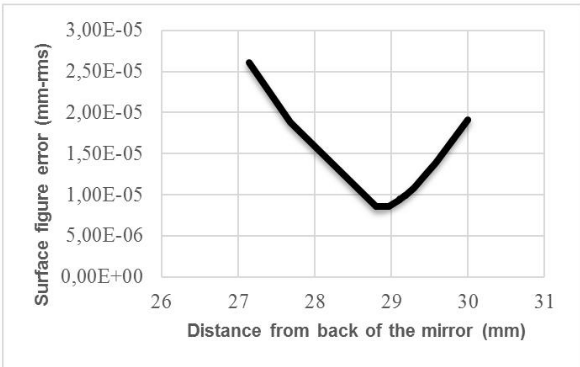


Figure 6. Variation of surface figure error with the support position.

Zernike polynomials are complete set of infinite number of orthogonal functions that are defined in a unit circle [8]. Surface deformation of the mirror is calculated with FEA (Finite Element Analysis) and transformed to Zernike polynomials to understand the nature of the deformations. 37 term Zernike Fringe coefficients are generated to describe the performance of the surface. First four terms are removed from analyses because they are indistinguishable from the alignment errors and can be corrected in the integration phase. With the help of Zernike polynomials, surface deformations are transferred to the optical simulation code and wavefront error originating from collimator mechanical design is obtained.

Three disturbance cases are evaluated with FEA models. In the first case, gravitational effects are considered. For the second case, temperature variations and resultant thermal strains are investigated within ±5°C temperature fluctuation. For the third case, effect of mechanical manufacturing errors and integration tolerances are investigated.

First, gravity induced deformations are investigated by finite element modeling. During the analyses, bipod surfaces touching to the baseplate are kept fixed. Gravity direction is shown in Figure 7. When gravity is applied, two bipods at the bottom are starting to push against the mirror while the top flexure starts to pull the mirror. These pushing and pulling forces are balancing the mirror weight and also generating deformations on the precise surface of the mirror as shown Figure 8. By only considering the deformations parallel to the optical axis, Zernike polynomials are calculated. WFE is calculated to be 4.89nm-rms after removing terms which are related to rigid body motion of the mirror.

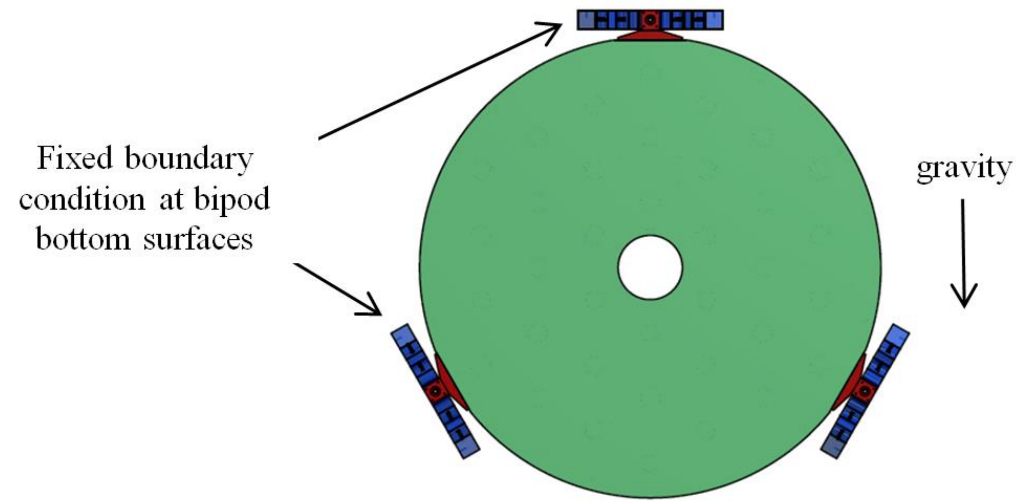


Figure 7. Gravitational loading of the M1 mirror.

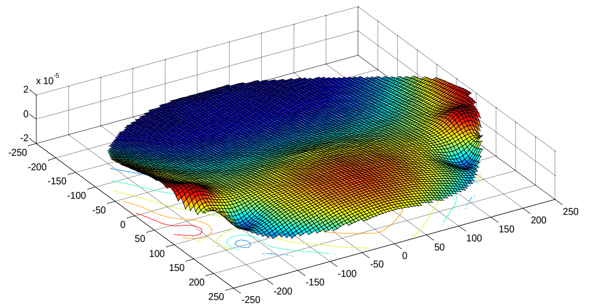


Figure 8. Gravity induced deformation on the mirror surface. (WFE = 4.89 nm-rms).

In the optical design, M1 surface is redefined using calculated Zernike terms resulted from finite element analyses. Collimation performance is obtained for different fields as shown in Figure 9. For all fields, gravity effects are not so high and for the first three fields all the rays are hitting into the diffraction limit circle. This means that mounting and mechanical design of the mirror successfully reduces gravity induced deformations.

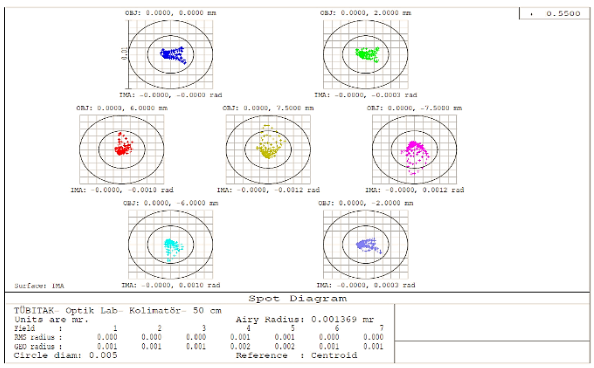


Figure 9. Collimation performance under gravitational loading.

In the second case, all the parts forming the collimator are heated up 5 °C. As a result of high thermal expansion coefficient, expansion of aluminum base plate is much more than the Zerodur mirror. In the analysis, collimator structure freely expands with the increase of uniform temperature. Thermally generated surface deformation is shown in Figure 10. As expected, a trefoil shape surface deformation is obtained which are concentrated around the mount positions.

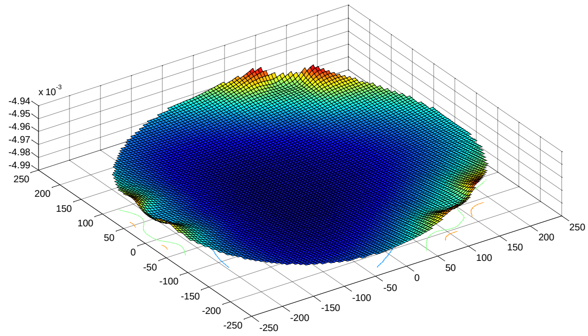


Figure 10. M1 surface deformations due to temperature increase of 5°C.

After removing first order terms related to rigid body motions, collimation performance is evaluated. Calculated surface deformation because of temperature difference is 3.15 nm-rms and resultant collimation spot diagrams are shown in Figure 11.

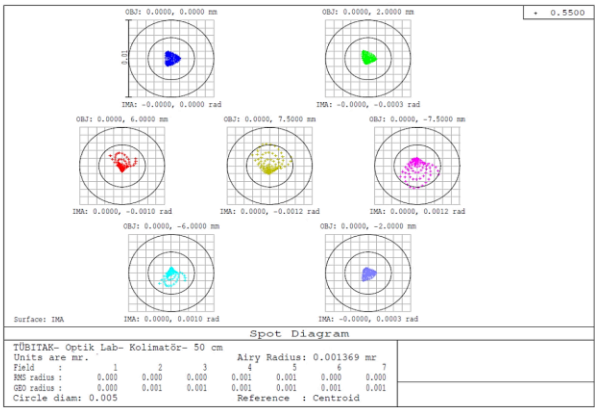


Figure 11. Collimation performance with temperature increase.

In the third case, the manufacturing and integration tolerances are considered. Intentional displacements are introduced to the bipod legs and surface deformations are generated. Displacement values ±200 microns for the radial direction, ±50 microns for the tangential direction and 20 microns for the optical axis direction are applied to each bipod leg. Many cases are created within the defined displacement ranges. The worst surface deformation is obtained as 7.16 nm-rms. M1 surface deformations are shown in Figure 12. Zernike coefficients are imported to optical software and collimation performance is evaluated (Figure 13).

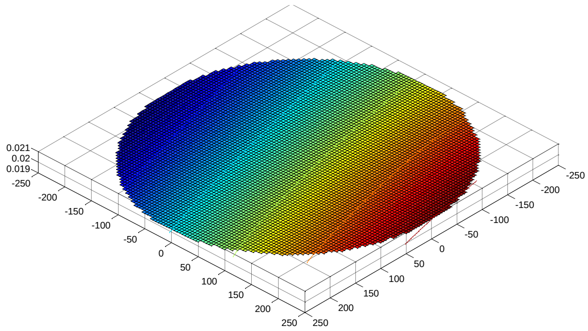


Figure 12. M1 surface deformation as a result of manufacturing and integration errors.

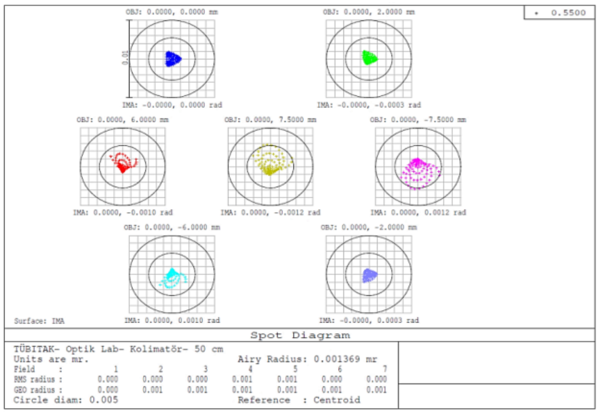


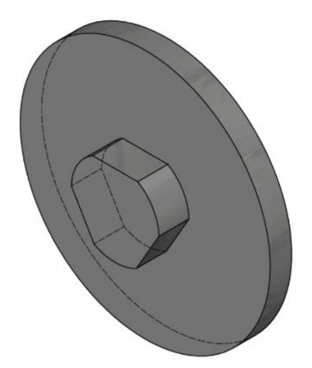
Figure 13. Collimation performance with manufacturing and integration errors.

Results obtained from all three cases are summarized in Table 2 for primary mirror assembly. The combined effects of deformations are consolidated with Root Sum Square (RSS) and 9.06 nm- rms total WFE is obtained. If the mirror is polished with respect to the mounted measurements, then for the calculation of the RSS deformation, gravity effects can be omitted. In this case maximum RSS surface deformation will become 7.82 nm-rms.

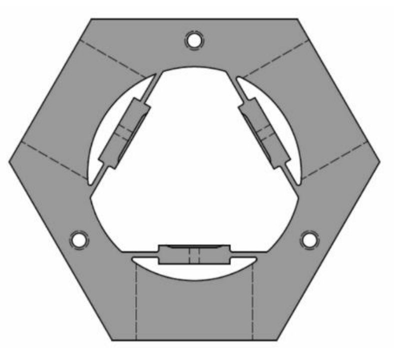
Table 2. Summary of surface deformations.

CASE	WFE
Gravity effects	4.58 nm-rms
Temperature increase	3.15 nm-rms
Manufacturing and Integration	7.16 nm-rms

M2 is a Zerodur mirror with a mushroom shape. Mounts of M2 mirror is manufactured similarly to M1 bipod mounts from invar with post heat treatment to compensate temperature variations (Figure 14). Because this mirror is very small with respect to M1, gravity induced surface deformations are very small for this optical component and can be ignored.



(a)



(b)

Figure 14. (a) M2 and (b) its flexural mount.

For M2 mirror, a flexural alignment mechanism will be used in order to correct positional errors originating from manufacturing and integration of the telescope structure. Two complementary flexural positioning stages are designed to move the secondary mirror at the alignment phase. First part is used for in-plane translational motion (Figure 15a) and second part is used for tip and tilt adjustment (Figure 15b).

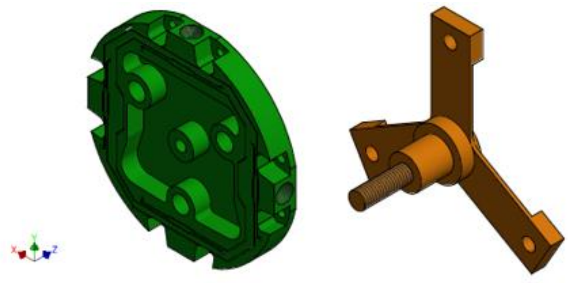


Figure 15. (a) M2 Flexural stage moving in the X-Y plane and (b) flexural stage for tip-tilt motions.

4. FABRICATION AND ASSEMBLY

Surface figures of large optics can dramatically degrade after attaching the mechanical holders. Holders can introduce permanent stress as a result of shrinkage of the adhesive during curing. Moreover, gravity can bring repeatable localized stress distribution and cause warpage of the optical surfaces. In high precision applications, these static and permanent disturbances are removed at the polishing phase by measuring the optics in its final mounts. Collimator mirrors are measured on their mounts during their manufacturing phase to eliminate the effects of bonding and gravity. Computer generated holograms (CGH) are used in the measurement setups to adjust spherical wavefront of the interferometer to match with the aspheric optical surfaces.

Final WFE obtained for the M1 mirror is 7.8 nm-rms as shown in Figure 15a. Measurements have been conducted on uncoated mirrors to improve the fringe contrast with a HeNe interferometer that is working at 633 nm wavelength. M2 mirror is also measured with similar methods and the results are presented in Figure 15b. Final measurement results are well below the requirements (<20 nm-rms WFE). Mirror is attached to and removed several times from its mounts to perform polishing, interferometric measurement and integration. Repeatable WFE performance is a proof of achieved proper mount design (Figure 16).

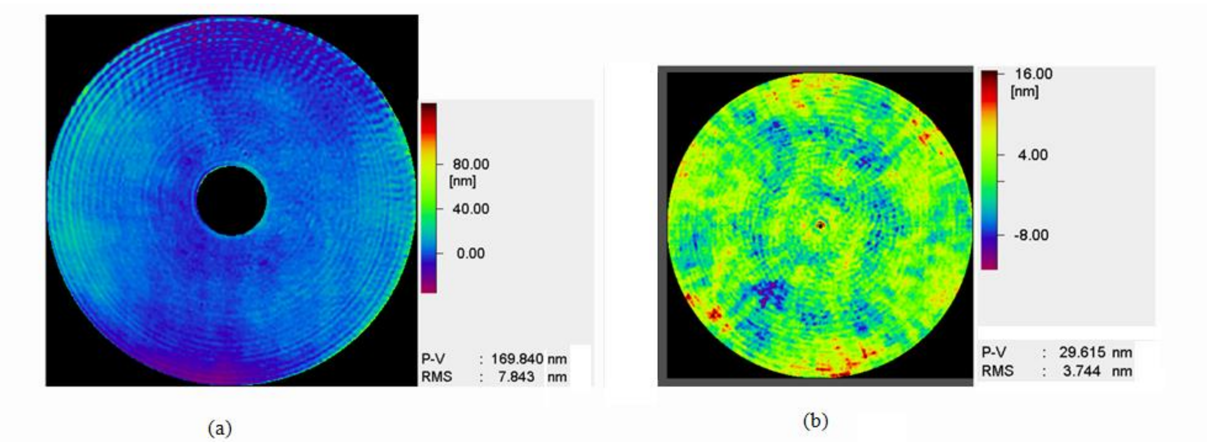


Figure 16. Interferometric test results for (a) M1 and (b) M2.

*M*anufacturing of mechanical mirror mounts are as important as the fabrication of mirrors in order to achieve overall performance requirements. Manufacturing and handling aspects of delicate mechanical parts should be considered in the design phase. Stress relief in the integration and protection of the manufactured parts during fabrication are important to fulfill planarity requirement between baseplate and M1 flexures.

5. INTEGRATION AND TESTS

Manufactured mirrors are successfully placed into the telescope structure (Figure 17) by using special handling tools and fixtures without risking the high precision mirrors. After first integration, relative positioning is measured to be less than 30 µm for Secondary mirror with respect to Primary mirror; which is a good positional accuracy for starting more accurate interferometric alignment [9].

Figure 17. Integrated collimator ready to interferometric alignment.

Final alignment of the telescope is performed with a double pass interferometer setup (Figure 18). In this setup, laser light generated by interferometer enters the collimator from the focal plane. Beam passes through collimator and bounces back from reference flat mirror and returns back to the interferometer with the same optical path. Using the interferometer data as a feedback for the optical performance, alignment mechanism on the secondary mirror assembly is used to accurately position the secondary mirror with respect to the primary mirror.

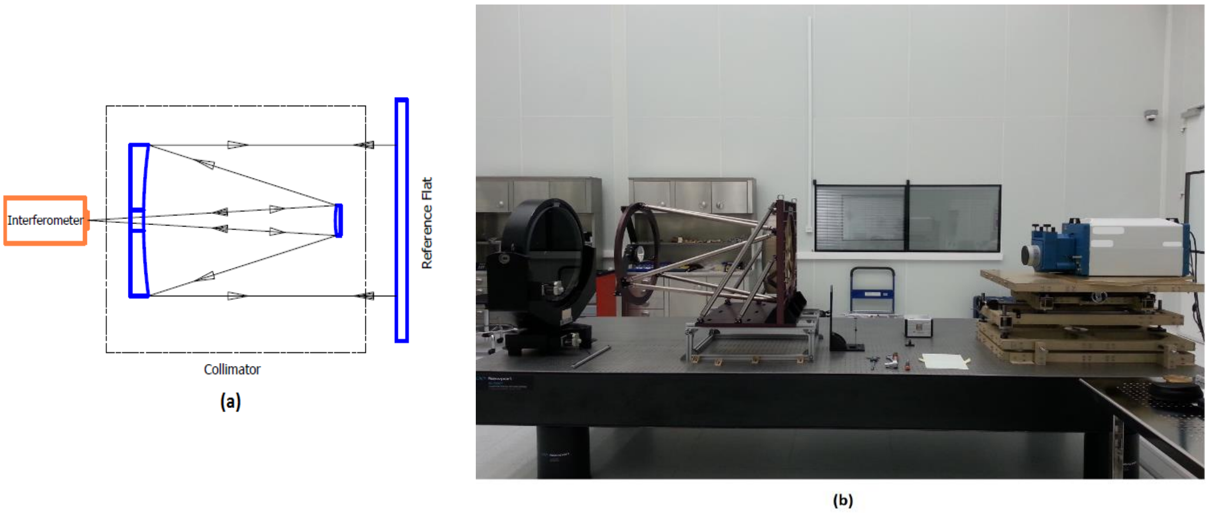


Figure 18. (a) Schematic of double pass interferometric setup, (b) Alignment setup for the Collimator.

6. CONCLUSION

A high precision collimator is developed to be used on measurement setups of satellite imagers, solar concentrators and similar high precision optical instruments. To serve different measurement setups a multi-configuration design is performed where the large concave mirror is to be kept fix in all configurations. Repeatable interferometric measurements performed on optical components are evidence for the proper mount design strategy applied to the development of the sub-assemblies. Collimator telescope has been integrated initially by the help of a coordinate measuring machine and then optical quality is improved with the final interferometric alignment.

Aknowledgements

This work is supported by Ministry of Development in Republic of Turkey under the contract name İMECE.

This study was partially presented in the Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation Conference, 2016.

REFERENCES

[1]. Yang H.S., Kang M.S., Kim S.H., Lee Y.W., Lee J.H., Song J.B., Lee H.Y., Kim S.W., Lee J.U. and Lee I.W., Development of Cassegrain type 0.9-m collimator. Proc. SPIE 5869 Optical Manufacturing and Testing VI, 586913, 2005.

[2]. Bin Z., Xiaohui Z., Cheng W. and Changyuan H., Computer-aided alignment of the complex optical system. Advanced optical manufacturing and testing technology, Proc. of SPIE 4231, 2000, 67-72.

[3]. Domínguez C., Antón I. and Sala G., Solar simulator for concentrator photovoltaic systems. Opt. Express 16, 2008, 14894-14901.

[4]. Fontani D., Sansoni P., Sani E., Coraggia S., Jafrancesco D., and Mercatelli L., Solar Divergence Collimators for Optical Characterisation of Solar Components. International Journal of Photoenergy, vol. 2013, Article ID 610173, 2013.

[5]. Chuanmin Z., Xu T., Liu S., Yang B., Liu Y., Design of primary mirror supporting structure and lightweigthing of space camera. Proc. SPIE 8416, 6th International Symposium on

Advanced Optical Manufacturing and Testing Technologies: Advanced Optical Manufacturing Technologies, 84161P, 2012.

[6]. Weingrod I., Chou C.Y., Holmes B., Hom C., Irwin J.W, Lindstorm O., Lopez F., Stubss D.M. and Wüesler J.P., Design of bipod flexure mounts for the IRIS spectrometer. Proc. SPIE 8836, Optomechanical Engineering 2013, 88360Q, 2013.

[7]. Hale L. C., Principles and Techniques for Designing Precision Machines. Ph. D: Thesis, 1999.

[8]. Chan C.Y., Chen Y.C., Chang S.T., Huang T.M. and Hsu M.Y., Design and analysis of isostatic mounts on a spaceborne lightweight primary mirror. Proc. SPIE 8836, Optomechanical Engineering 2013, 88360K, 2013.

[9]. Ekinci M. and Selimoglu O., Development of a 0.5m clear aperture Cassegrain type collimator telescope. Proc. SPIE 9912, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II, 991253, 2016.