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Designing Cassegrain Telescope System with Best Obscuration Ratio of Secondary Mirror

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Abstract

A computer simulation was conducted using Optics Software for Layout and Optimization (OSLO) to design a Cassegrain telescope system for on-axis rays. In order to establish such a telescope, the two mirrors of the optical system were designed as spherical surfaces: a concave mirror and a convex mirror. The obscuration ratios of the Cassegrain telescope's secondary mirror were examined using different values, which ranged between 0.1 and 0.3, to determine the best obscuration ratio. This work adopted three criteria to decide which obscuration ratio is the best for the Cassegrain telescope. The first criterion was the number of rays that reached the final image. The second criterion was calculating the modulation transfer function (MTF). The third criterion was calculating the point spread function (PSF) and Strehl ratio (SR). Finally, the result showed that the best obscuration ratio of the telescope's secondary mirror was found at D2/D1=0.116-0.166, where D1=0.76 m for the primary mirror and D2=0.09 – 0.125m for the secondary mirror.

Keyword: Cassegrain telescope, Obscuration ratio, PSF, MTF, Strehl ratio, Secondary mirror.

تصميم نظام تلسكوب كاسجرين مع افضل نسبة تعتيم للمراة الثانوية

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الخلاصة

في هذا العمل ، تم إنشاء محاكاة الكمبيوتر باستخدام Optics Software for Layout and Optimization (OSLO) لتصميم نظام تلسكو ب كاسجرين في حالة كون الأشعة على المحور. من أجل تصميم مثل هذا التلسكوب، تم اعتماد مرآتي النظام البصري كسطحين كرويين: مرآة مقعرة ومرآة محدبة. تم اختبار نسب تعتيم مختلفة للمرآة الثانوية لتلسكوب كاسجرين والتي تراوحت بين 0.1 و 0.3 لحساب افضل نسبة. تم اعتماد ثلاثة معايير لتحديد نسبة التعتيم الأفضل لتلسكوب كاسجرين. المعيار الأول هو عدد الأشعة التي تصل إلى الصورة النهائية. المعيار الثاني هو حساب معامل دالة التحويل (MTF). المعيار الثالث هو حساب دالة الانتشار النقطي (PSF) ونسبة ستريل (SR) . واظهرت النتائج ان أفضل نسبة تعتيم للمرآة الثانوية لتلسكوب كاسجرين هي من 0.116 الى 0.166 ، حيث ان قطر المراة الرئيسية 0.75م وقطر المراة الثانوية من 0.09 الى 0.125 م.

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1-Introduction

A telescope is an astronomical instrument used to gather light from the sky to observe celestial objects like planets, stars, galaxies, etc. Optical telescopes are classified into refractor, reflector, and catadioptric. The objective of a reflecting telescope is to create a mirror [1]. The Cassegrain telescope is the most significant form of reflecting telescope [2]. The Cassegrain telescope has a longer focal length and higher magnification [3]; the optical design of Cassegrain telescopes is based on Gascoigne's third-order analytic aberration theory [4]. The Ritchey-Chretien telescope is one of the Cassegrain telescope types with three focal points, making it useful for various observations. Furthermore, Cassegrain telescopes have many practical applications, such as the Chandra Telescope and the Hubble Space Telescope, that work in space.

The Cassegrain telescope has two types of mirrors: a concave mirror and a convex mirror. The primary mirror is housed at the bottom of the telescope's tube and is a parabolic concave mirror with a hole in the middle. The hyperbolic secondary convex mirror is smaller than the primary mirror and is located at the top of the telescope's tube, inside the focus of the primary mirror [5]; see Figure(1) [6].

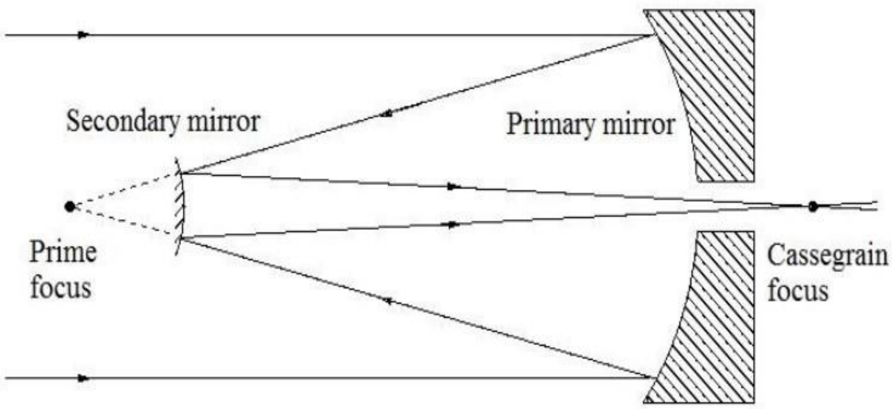

Figure 1: The Cassegrain telescope diagram [6]

The obscuration of the Cassegrain telescope reduces the total amount of light reaching the primary mirror. This may reduce the telescope's image quality and resolution performance. The amount of obscuration caused by the secondary mirror depends on the size of both mirrors. The smaller the secondary mirror, the less it will obscure the primary mirror and the better the telescope performance. It is essential to note some advantages of using a Cassegrain telescope with a secondary mirror. These telescopes are often more compact and more accessible to transport than others and can often provide good-quality images even with relatively small primary mirrors [7].

Some researchers proposed that aperture illumination shaping devices, like dual-shaped sub-reflector systems and shaped lenses, must be placed close to an image of the telescope aperture distribution [8]. Zacharias found a design solution to minimize obscuration and offered adjustment effectiveness for decentration, tilt, and focus using stepping motors to accomplish better translation, resolutions in focus, and tilt mode [9]. McLeod demonstrated a straightforward method for collimating the secondary mirror of Cassegrain telescopes. At these levels, it is significant precisely measure several diffraction causes, such as segmentation geometry effects, obscuration of the secondary mirror, the veins of the secondary mirror, figure errors, and other effects [10]. The objective of the work of Barcik et al. was to examine how the telescope's obscuration impacts the coupling performance of the photonic receiver [11].

2- Secondary Mirror Obscuration

The Cassegrain telescope's secondary mirror creates a shadow, which lowers the contrast and effective aperture performance. Any component in the telescope's optical path creates this shadow, called an obstruction. Therefore, the obstruction increases with secondary mirror size. To calculate the contrast performance of a telescope, one can subtract the diameter of the secondary mirror from the primary mirror diameter. This will increase the effective contrast aperture of the telescope without obstruction [12] [13] [14]. For example, the obstruction by the secondary mirror of HST is 0.128, where the primary light diameter is 2400 mm, and the secondary light diameter is 307.695 mm [14]. The research objective is to design a Cassegrain telescope with the best possible obscuration ratio for the secondary mirror using OSLO software. The third section will provide an overview of the optical configuration of the Cassegrain telescope. Section four will explain theoretical concepts such as Modulation Transfer Function, Point Spread Function, and the Strehl ratio. The results and their discussion will be presented in Section Five. Section six will conclude the work.

3- Configuration of the Cassegrain Telescope

The Cassegrain telescope is a reflecting telescope invented by Frenchman Laurent Cassegrain in the mid-seventeenth century. It has a concave primary mirror at the bottom of the telescope. The primary mirror is the largest and most important optical part of the Cassegrain telescope, as it determines the amount of light collected and the telescope's resolving power. On the other hand, the secondary mirror in the Cassegrain telescope is a convex hyperboloid mirror set up at the top of the telescope's tube inside the focus of the primary mirror and can be adjusted to correct the focus of the image the telescope produces. Light enters through the aperture of the telescope and is reflected from the primary mirror toward the secondary mirror. Then, light reflects off the secondary mirror before coming to a focus behind the primary mirror through a hole in its center, where an eyepiece or camera can observe the light. This design allows for a long focal length while keeping the tube shorter than a comparable refracting telescope. The f-ratio is usually between f/8 and f/15, resulting in a plate size suited to high-spatial-resolution images; it can accommodate large, cumbersome instruments [7] [15].

4- Theoretical Concepts

This section involves two parts are:

4.1 Optical Transfer Function (OTF):

It is a mathematical concept that describes how a telescope or a camera successfully transfers an object into an image. OTF is a complex-valued function that explains how an optical system responds to spatial frequency; it is calculated using the Fourier transform of the point spread function or the pupil function's auto-correlation. It consists of phase and magnitude components. Modulation Transfer Function (MTF) and Phase Transfer Function (PTF) are two terms used to describe the OTF [16], as follows:

$$OTF = MTFe^{iPTF} \tag{1}$$

The resolution of the optical system, which is often expressed in line pairs per millimeter (lp/mm), determines how much detail is present in an image; a line pair is a cycle of bright and dark bars with the same width and contrast. Comparison is described as

$$contrast = \frac{I_{max}-I_{min}}{I_{max}+I_{min}} \tag{2}$$

I_{Max} is the maximum intensity, and I_{Min} is the minimum intensity an image produces. A plot of contrast versus spatial frequency represents MTF. This graph is usually normalized to a value of one at zero spatial frequency [16] [17].

4.2 Point Spread Function (PSF) and Strehl Ratio (SR):

The point spread function (PSF) describes an imaging system's responses to a light point source. The PSF has a complex structure as its shape depends on the optical path of the light through the atmosphere and many optical devices such as mirrors, lenses, and detectors [18] [19] [20].

By considering light as a wave, the PSF can be described mathematically. An astronomical image of point sources is affected by the distribution of light intensity, and this effect is determined by the aperture's shape, obstacles, diffraction effects, and geometrical aberrations. These components might be combined into a specific term, complex pupil function [21], which is defined as:

$$P(r,\varphi)e^{ikW(r,\varphi)} \quad (3)$$

where k is the wave number, W (r, ϕ) represents the wavefront error, and P (r, ϕ) represents the transmittance of the aperture. P (r, ϕ) is one for unobscured areas of the aperture and zero for obscured regions. The PSF of the image is calculated by using the two-dimensional Fourier transform of the complex pupil function [22].

The Strehl ratio is the ratio of an observed PSF's normalized peak diffraction intensity to the perfect image. In other words, the ratio compares the image quality value in the presence of aberrations in a real system to the image quality value in an aberration-free system, called diffraction-limited [23]. When designing an optical system, the Strehl ratio determines how much wavefront aberration correction is required. The degree of tolerable wavefront aberration depends on the application; however, 0.80 Strehl is commonly used to classify an optical system as diffraction-limited or ideal.

5- Results and Discussion

This section will present the results from this work in a detailed description in line with the methodology adopted.

Figure (2) shows the number of rays passing through the aperture for every chosen obscuration ratio. The number of rays is the first criterion to determine the best obscuration ratio. Also, the figure shows the total number of rays and the number of obscure rays by the secondary mirror. Figure (3) shows the ratio of rays reaching the final image as a function of the obscuration ratios (D_2/D_1). The best ratio, which allowed the highest number of rays to get through the aperture and reach the final image, was 0.116. The total number of rays was 917, and the rays that reached the image were 908, so 99.2% of the rays passed through. Figure (4) shows the ray tracing of the Cassegrain telescope.

Figure (5) shows the maps of the ray's intersection, where the ratios 0.1 and 0.3 did not produce an image, so they were considered bad ratios for designing a Cassegrain telescope. In the case of the 0.1 ratio, the number of rays reflected from a small secondary mirror can not produce a clear image. Whereas, in the case of a 0.3 ratio, the rays can not reach the objective mirror because of the obscure secondary mirror. Other sub-figures show the maps of intersections of rays for ratios 0.116, 0.133, 0.1666, 0.2, 0.233, and 0.266.

Table 1 illustrates the modulation transfer function for different obscure ratios of the secondary mirror (0.116-0.1666, 0.2, and 0.233-0.2833) and the diffraction-limited MTF. The diffraction-limited MTF is the maximum performance of an optical system, where the effects of aberrations were assumed to be negligible. The results were obtained using OSLO software and illustrated in Figure (6), plotted in green.

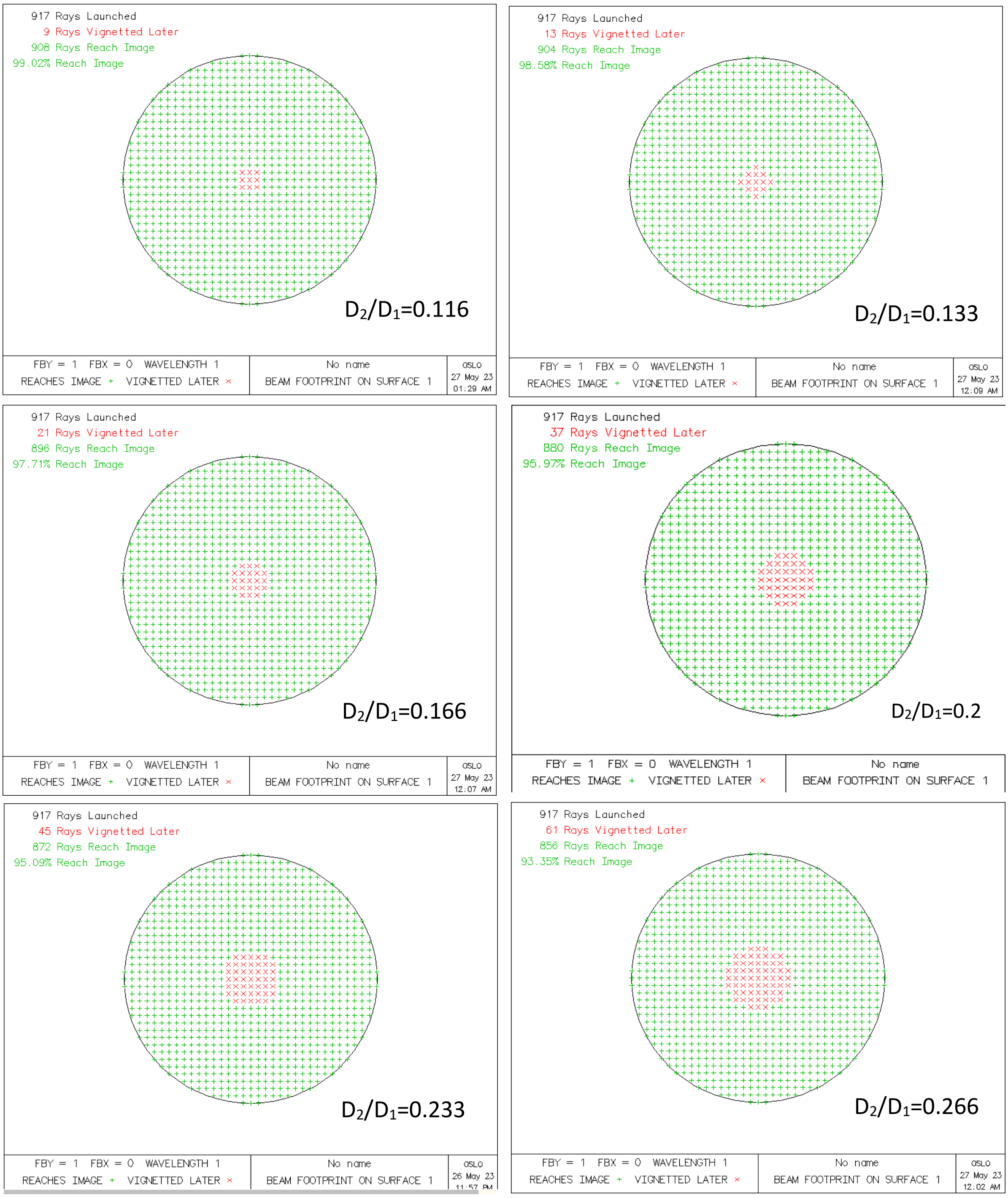

Figure 2: Shows the beam footprint for different obscuration ratio of the secondary mirror

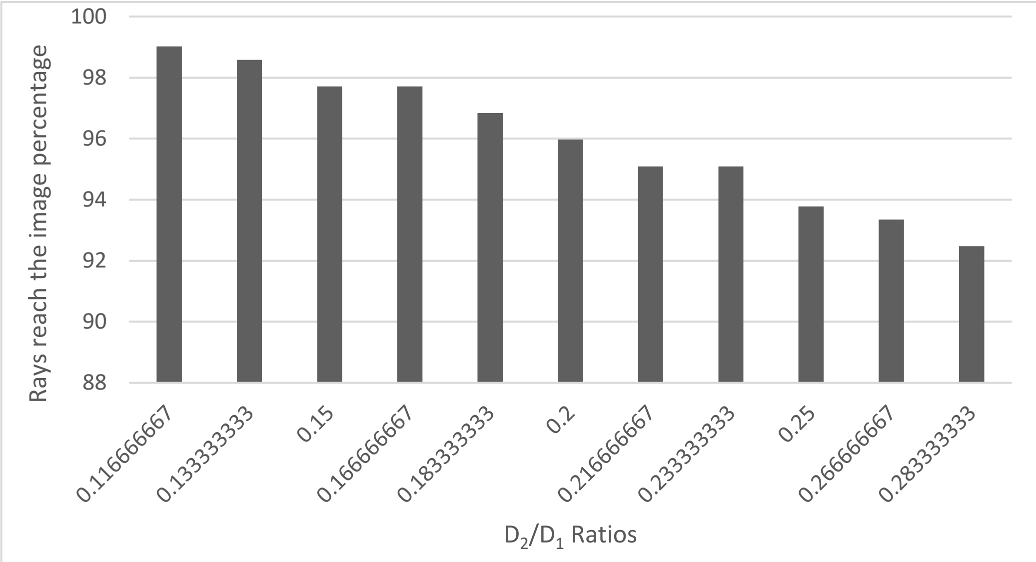

Figure 3: Shows the ratio of rays reach the final image as a function of the

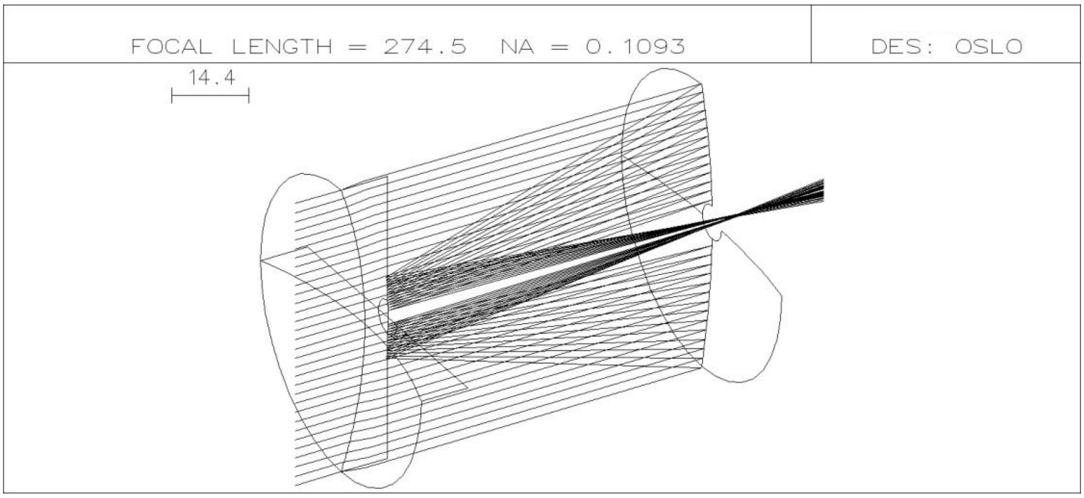

Figure 4: Shows the ray tracing of the Cassegrain telescope by using OSLO software

Figure (6) shows the MTF on the y-axis. MTF is labeled the modulus of OTF, where OTF represents the optical transfer function. On the x-axis, the frequency in cycles per millimeter goes from zero, which represents low spatial frequency, all the way up to 245 cycles per millimeter, which represents high spatial frequency. The cutoff frequency was 403.622. In the top left of Figure (6), all the lines began at 1, then split at 24.5 cycles/mm.

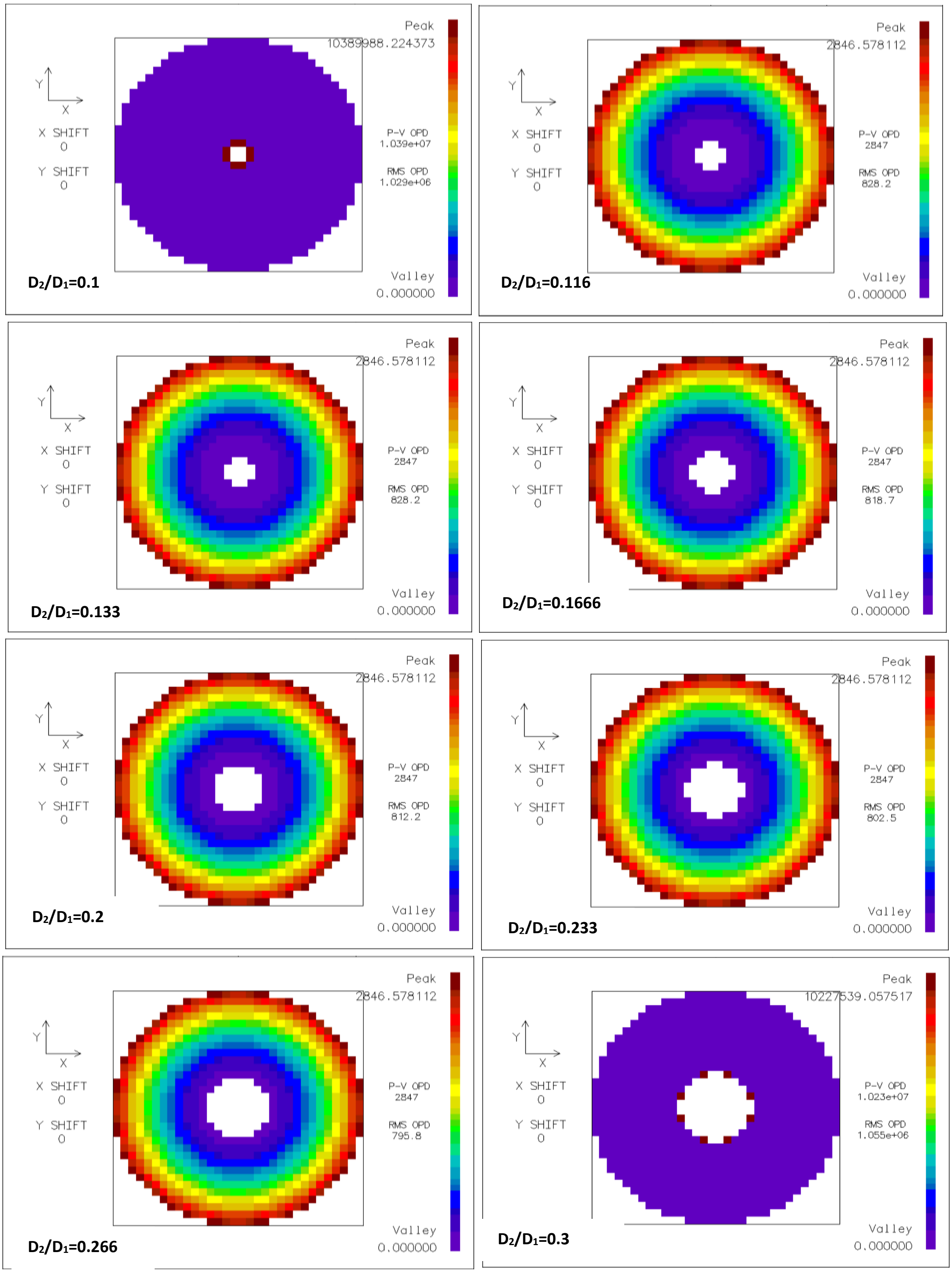

Figure 5: The maps of the intersection of rays for different obscuration ratios

Table 1: Illustrates the Modulation transfer function for different obscuration ratios

	FREQUENCY Cycles/mm	Modulation Transfer Function (MTF)			
		0.116- 0.166	0.2	0.233	Diffraction limited
1	0	1	1	1	1
2	24.5	0.870518	0.853385	0.850716	0.87942
3	49	0.747561	0.713756	0.701797	0.771984
4	73.5	0.638339	0.593211	0.570912	0.67552
5	98	0.535733	0.487388	0.466149	0.579056
6	122.5	0.444405	0.410252	0.395074	0.486917
7	147	0.368562	0.350167	0.342155	0.40739
8	171.5	0.294842	0.286553	0.285138	0.328114
9	196	0.224506	0.225171	0.224465	0.249019
10	220.5	0.165027	0.167383	0.167716	0.184722
11	245	0.115854	0.118598	0.120794	0.132109
	Strehl ratio	0.912914	0.917309	0.919564	
		CUTOFF FREQUENCY 403.622276			

The green line represents MTF for differentiation limited; the blue line represents 0.116-0.1666 ratios; the red line represents a 0.2 ratio; and the yellow line represents a 0.233 ratio. This figure of MTF shows how well this optical system (obscure ratios D_2/D_1) performs to a spatial frequency of cycles per millimeter. It can show how well the mirrors can reproduce their objects using the MTF. The higher the MTF lines, the better the object can reproduce an image. The lower the MTF lines, the worse the object can reproduce an image. So, the red line gives the best result compared with the other lines (blue and yellow lines). At the same time, the green line is the best result of the aberration-free optical system. From Table (1), Strehl ratios for all the obscuration ratios of the secondary mirror, which were calculated using OSLO software, were higher than 0.8, so the optical design of the Cassegrain telescope does not suffer from aberration effects. From Table (2), PSFs of the ratios 0.116, 0.133, and 0.166 showed better results than PSFs of other ratios, 0.2, 0.233,0.233, and 0.266. Therefore, this mphasizes that the best obscuration ratio for the secondary mirror was 0.116, 0.133, and0.166.

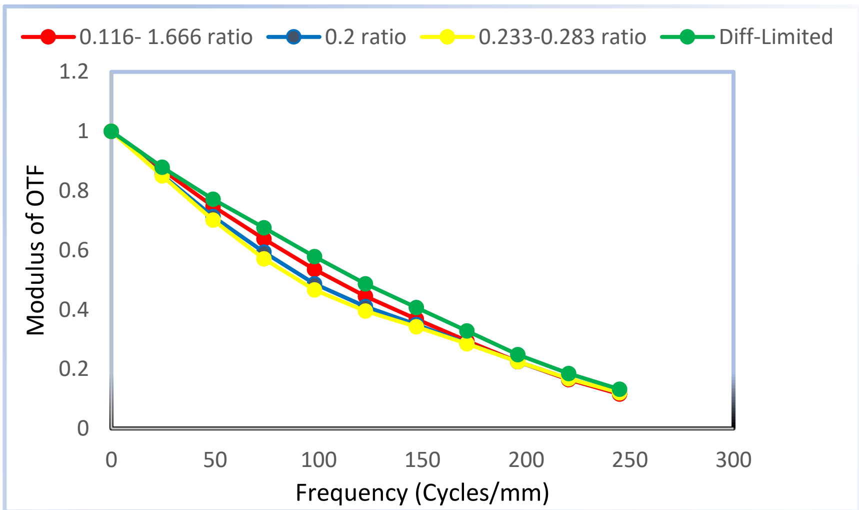

Figure 6: Shows the modulus of OTF as a function of frequency

Table 2: Illustrates the point spread function for different obscuration ratios

Ratios	PSF
0.116, 0.133, and 0.166	0.096869
0.2, and 0.233	0.093402
0.266	0.090495

Conclusion:

An on-axis, two-mirror-based telescope design was presented in this paper. The telescope's design used primary and secondary mirrors with an obscured aperture to test the best ratio of obscuration for the secondary mirror. This design produced a compact optical system of two mirrors obscured Cassegrain telescope, with a resulting image quality close to the diffraction limit. To reach this goal, three criteria were used to examine the design, which will conclude as follows: The Strehl ratio for all tested ratios is excellent, so it can be confidently said that the image quality does not suffer from a considerable aberration effect. The MTF plot for the obscuration ratio that was shown in Figure (6) is very close to the diffraction-limited MTF plot. Some ratios, for example, 0.116, 0.133, and 0.1666, gave better results at some frequencies (24.5–171.5) than the others, 0.2–0.266. At frequencies higher than 180 cycles/mm, obscuration ratios 0.2, 0.233, and 0.266 gave better results. Figure (2) shows the number of rays that reach the final image, and the best result was obscuration ratios of 0.116-0.1666 with 99.02% of the incident rays. Table (2) shows that the PSFs of 0.116, 0.133, and 0.1666 ratios gave better results than others. It can be concluded that the best obscuration ratio for the secondary mirror is 0.116, 0.133, and 0.166.

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