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ORIGINAL ARTICLE

A Computer Simulation of Hubble Telescope Including Eyepiece Nano-Sensors to Increase Optical Efficiency

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ABSTRACT

The Hubble telescope is characterized by the accuracy of the image formed in it, as a result of the fact that the surrounding environment is free of optical pollutants. Such as atmospheric gases and dust, in addition to light pollution emanating from industrial and natural light sources on the earth's surface. The Hubble telescope has a relatively large objective lens that provides appropriate light to enter the telescope to get a good image. Because of the nature of astronomical observation, which requires sufficient light intensity emanating from celestial objects (galaxies, stars, planets, etc.). The Hubble telescope is classified as type of the Cassegrain reflecting telescopes, which gives it the advantage of eliminating chromatic aberration. Zemax optical design program was used to simulate the design of the Hubble telescope with nanosensors eyepiece, and to evaluate its performance through a set of analysis tools in the program, by changing some of the optical parameters that affect the performance of the telescope.

The results proved needing of the imaging optical system (telescope) to align the observed object to avoid off-axial aberration. When the angle of incidence of the rays is changed to an appropriate extent, the image is negatively affected as a result of the increase in the amounts of aberration in it. The simulation also showed the similarity of the optical parameters that are related to the engineering design to get the best picture, through the analysis tools used in the program.

Keywords: Reflective telescope, Nano sensors, Hubble, optical efficiency, Zemax program.

INTRODUCTION

The process of astronomical observation of celestial objects requires sophisticated devices that produce good images of the observed objects, even if they are far away. Hence, human need to develop astronomical observatories to obtain the best images [1]. Despite the technical and environmental problems that accompany with astronomical observation, science has made great strides in developing telescopes of all kinds. The problems facing astronomical observation include the aberration and diffraction formed in the image, in addition to the factors of humidity, dust and light pollution associated with the atmosphere [2].

Extraterrestrial telescopes of is effective in overcoming the environmental problems that accompany astronomical observation. Where the telescope is placed in Earth orbit as a satellite, and it is linked to the ground station with high-tech communication and data transmission devices, as in the Hubble telescope, or it is outside the earth's influence in a region of gravitational equilibrium between the earth and the sun (Lagrange point), as in the James Webb telescope. The telescope produces clear and high-resolution images despite the relatively large dimensions of the observed objects[3].

This observatory's orbit is outside the Earth's atmosphere scattering light from cosmic bodies, allowing for high-resolution images with almost no background light. For example, the Hubble Deep Field image is the most detailed visible spectrum image ever taken of the universe's most distant objects. Many Hubble telescope observations have led to surprising advances in astrophysics, such as the law of exact determination of the expansion rate of the universe [4].

The Hubble Space Observatory is one of the largest and most diversified space observatories, although not the first among them, and is well known as a vital research tool in astronomy. Compton Gamma-Ray Observatory, Chandra X-ray Observatory, and Spitzer Space Telescope [5].

The Hubble telescope is a reflecting telescope (Cassegrain Telescope), which contains two aspherical mirrors. The primary mirror (annular) facing the light emanating from the observed object to reflect the light to the secondary mirror whose reflecting surface faces the primary mirror, to reflect the light to the central aperture of the primary annular mirror to reach the eyepiece Nano-sensor to receive the image [6].

The traditional observation by the naked eye is replaced by a Nano-sensor attached to a digital camera. The Nano-sensor is characterized by high sensitivity to a broad range of wavelengths (infrared and visible light), due to the presence of Nano dots that produce quasi-energy levels in atoms that give a broad range of the absorption spectrum of photons[7].

The spectrum of the Hubble telescope is in the near ultraviolet, visible light, and near infrared range. Observations in telescopes are often in the visible light field due to the engineering design of the telescope and the presence of aspherical mirrors with a relatively large aperture diameter that provide appropriate light photons to obtain a high-resolution image free of chromatic and monochromatic aberration [8].

The Hubble telescope includes a set of complementary auxiliary devices that contribute to improving the performance of the telescope and self-maintenance because it is in a location relatively far from human reach. These devices are; wide Field and planetary camera, Goddard high resolution spectrograph, high speed photometer, faint object camera and faint object spectrograph [9].

The Hubble Telescope is characterized by the absence of lenses in it (it contains mirrors only), and this does for several reasons: the size of the large telescope requires the manufacture of a large lens, and this is an industrial matter, and the large lens may contain air bubbles or industrial defects that reduce the quality of the image, and the light can be lost while passing through the lens as a result of refraction, the lens produces chromatic aberration due to the phenomenon of dispersion, which leads to distortion in the features of the image, and finally, the large weight of the lens represents a logistical and technical problem that hinders the function of the telescope [10].

There is a several studies related to Cassegrain telescopes in general and the Hubble telescope in particular, as it is one of the important topics in astrophysics. A Cassegrain telescope was designed (in 2020) to works within the range of infrared and radio waves using a flat mirror instead of a spherical mirror that works on circular polarization of light [11].

A Cassegrain telescope has been designed for optimization of telescope to detect explosives remotely for laser-induced breakdown spectroscopy (LIBS) (in 2017). A design optimization of Schmidt corrector plate was carried out for Nd:YAG laser. Effect of different design parameters was investigated to eliminate spherical aberration in the system. Effect of different laser wavelengths on the Schmidt corrector design was also investigated for the standoff LIBS system [12].

In (2012), the design considerations for astronomical space telescopes was covered of many disciplines but can be simplified into two overarching constraints: the desire to maximize science while adhering to budgetary constraints. More than ever, understanding the cost implications up front will be critical to success [13].

A study was conducted about the Hubble telescope (in 2012) and its working mechanism by presenting all the optical parameters of the design engineering. And all the problems that encountered the initial design, and methods of correcting the image during NASA's trips to space [14].

Astronomical object observed through a telescope with a finite aperture will create a diffraction pattern (aberration free), the effect limits the image resolution. The larger aperture of the telescope, the better the resolution (the fainter the objects it recognizable) [15]. The resolution of an astronomical telescope is defined to be the smallest angular separation of two point sources of light that will allow them to be resolved as individual point sources, despite their overlapping diffraction patterns. The exact point at which two adjacent diffraction patterns are overlapping is a bit vague, but one commonly used definition is the Rayleigh criterion. Under the Rayleigh criterion, the smallest angular separation θ that two point sources can have and still be resolvable as two individual point sources is [16]:

$$\theta = 1.22\frac{\lambda}{D} \quad \dots(1)$$

where θ is the angular resolution in radians, λ is the wavelength of the light, and D is the diameter of the aperture of the instrument. For the Hubble Space Telescope, (D = 2.4 m), and λ varies between (100 and 2500 nm).

The most important parameter used in imaging optical systems in general and telescopes in particular is the focal number (f-number; f/#). The focal number is the ratio between the focal length and the diameter of the aperture. The aperture diameter of the telescope is (2.4m) and the focal length is (57.6m). So the value of the focal number is equal to [17]:

$$\mathrm{f-number} = \frac{f}{D} \quad \dots(2)$$

For Hubble telescope, the primary mirror has an f-number of f/24.

Optical Design: The Hubble telescope consists of two reflecting surfaces of one optical axis (primary and secondary aspherical mirrors) facing each other. The primary mirror is a large annular mirror with a diameter of (2.4 meters) that allows an appropriate amount of light to enter the telescope, to be reflected to the secondary mirror, which is relatively small with a diameter of (0.28 meters), to reflect the light back to the central aperture in the primary mirror to collect light in the eyepiece lens as shown in figure (1). Then the light is transmitted to the camera to produce the image. The length of the Hubble telescope is about (6.5 meters) to match the effective focal length of the telescope, which arises from the design of reflecting mirrors with a radius of (-4.9 meters) for the primary mirror, and a radius of (-4.6 meters) for the secondary mirror [18, 19].

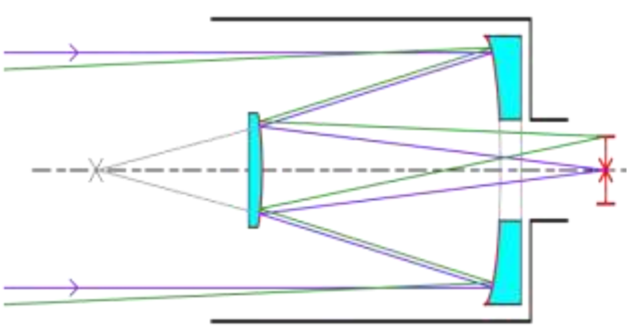

Figure 1: the internal components of Hubble telescope [15]

A simulation of the Hubble telescope was carried out using the Zemax Optical Design Program, by entering all the optical parameters of the telescope to obtain a virtual design that simulates the original device. The purpose of using the Zemax program is to study and evaluate the images generated by the telescope through a set of analysis tools provided by the program. These tools give a clear idea of the quality of the image formed in the telescope by measuring the amount of aberration, the scattering pattern of the rays in the image plane, the distribution of the light energy of the photons, and the amount of contrast in the image according to the spatial frequency function [20].

Zemax program provides a set of image analysis tools, including spot diagram, point spread function PSF, ray fan aberration curve, optical path difference OPD, optical transfer function OTF, and encircled energy. The spot diagram tool represents the distribution pattern of light rays in the image plane of a point object, according to a standard of ideal image called Airy pattern (Airy disk) [21]. Airy disk occupies an area equal to (80%) of the light rays, so can judge the quality of the image by limiting the rays in this range.

The most important tools that determine the type and amount of aberration occurring in the optical system are the ray fan aberration curve and OPD [22]. The aberration curve defines the projections of the rays on the sagittal and tangential axis (Y, X axis) in the image plane to give a curved shape in the form of a fan, representing the amount of its curvature and its distance from the horizontal axis the amount of aberration occurring in the image [23]. As for OPD, it represents the change in the wave front's path from the original path. The path difference gives the amount of distortion that occurs in the shape of the wave front.

OTF represents the amount of contrast in the image according to the spatial frequency, to give a clear idea of the image quality by measuring the curve of the function that is inversely proportional to the amount of the spatial frequency. PSF shows the amount of radiation distribution of the point object in the image plane according to the Strehl criterion [24], which gives an optimum value for a good image of (85%), PSF gives the shape of the diffraction pattern formed in the image plane (in case the optical system is free of aberration). The pattern is in the form of a central peak that includes most of the image intensities according to the Strehl criterion, then small secondary peaks that include the remaining intensities[24].

The encircled energy curve is useful in evaluating the image formed in imaging optical systems, and the distribution of radiant energy in non-imaging optical systems. It occupies a circular (or a square) sectors starting from the center until it reaches the edges of the image plane. The light energy is calculated from the center to the edges in the cumulative form of the energy value, so that the curve starts from zero and rises sharply when the radius of the image area increases until it reaches a constant value no matter how much the radius value increases.

RESULTS AND DISCUSSION

The imaging optical systems change dramatically with the change in the angle of incidence, any small change in the path of the light rays from the optical axis clearly affects the quality of the image. due to the appearance of off axial aberration. Therefore, these systems need a light collimator that matches the location of the object with the optical axis to get the best image. The effect of changing the angle of incidence of light rays on the telescope has been included by (0^o, 0.1^o, 0.2^o, 0.3^o, 0.4^o, 0.5^o). Where the angle changes towards the x-axis from the optical axis.

Figure (2) shows the spot diagram in the image plane of the Hubble telescope when using variable values of the angle of incidence. The figure shows the extent of variation in the distribution of rays in the image plane when the angle of incidence changes due to the appearance of off axial aberration. The Airy disk radius values are included in the spot diagram for all cases. The ideal value of the Airy radius is (14.64µm) to be a criterion for the ray distribution diagram for the mentioned cases, so the values of the Airy RMS radius are (0.001, 11.525, 46.88, 116.63, 265.55, 607.50 µm) for the amount of the angle of incidence (0^o, 0.1^o, 0.2^o, 0.3^o, 0.4^o, 0.5^o) respectively. It is clear that the optimal value of the rays distribution at the angle (0º) due to the very small rays distribution area (0.001µm) compared to the area of the Airy disk. An acceptable image is also formed at the angle (0.1º), however the area of distribution of the rays gradually increases as the angle of incidence increases to reach an unacceptable level.

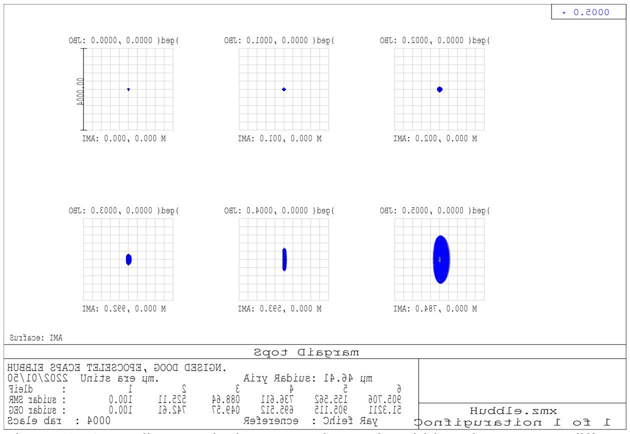

Figure 2: Spot diagram in image surface of Hubble telescope at different incidence angle

The ray fan aberration curve shows the projections of the light rays on the sagittal and tangential axes in the image plane. Where the inclination of the curve from the horizontal axis represents the amount and type of aberration occurring in the image. In the ideal image, the intersection of the rays is produced at the focal point, to extend the rays after this point on two axes (sagittal and tangential) to give a straight shape that matches the horizontal axis. In the case of spherical or coma aberration, the rays extend on the two axes diagonally to give a curved shape (fan), so the amount of curvature in the curve represents the amount of aberration in the image.

Figure (3) shows the curve of the aberration occurs in the image plane of the telescope for different values of the angle of incidence. When the angle value increases, the slope of the curve gradually increases away from the horizontal axis of the sagittal and tangential planes (Y and X axis), but the curvature of the saggital plane is greater (X axis) because of the slope of the angle of incidence on the same side, so the tilt of the axis is affected more than the other. The increase in the inclination of the curve is a result of the increase in the axial aberration in the image as the object exits from the optical axis. Therefore, any slight change in the alignment of the object with the telescope will affect the quality of the image.

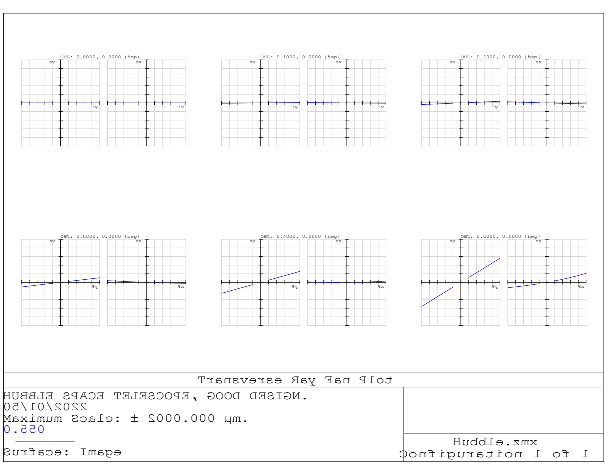

Figure 3: Ray fan aberration curves in image surface of Hubble telescope at different incidence angle

The difference in the optical path shows the extent of the change in the spherical path of the wave front after reflection or refraction (from the lens or mirror). The amount of curvature in the OPD curve represents the amount of distortion in the wave front due to a change in its path due to aberration. Figure (4) shows the OPD function in the image plane of the Hubble telescope when the angle of incidence changes at certain values. The figure shows the increase in the curvature of the function with the increase in the angle of incidence due to the increase in aberration.

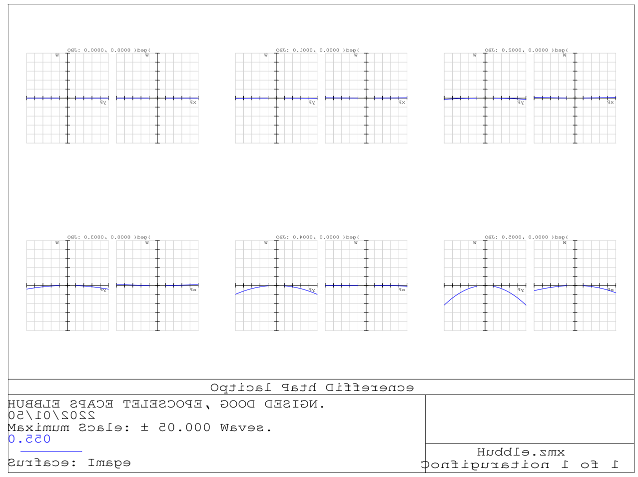

Figure 4: OPD in image surface of Hubble telescope at different incidence angle

Modulation transfer function represents the normalized value of OTF that gives maximum value of the function equal to (1). MTF gives a clear idea of the quality of the image formed in the optical system. An ideal system without aberration (diffraction limited) is MTF in the form of a line with smooth curvature, starting from the maximum value of the function (1) and ending to the minimum value (0) when the value of the spatial frequency is increased. Increasing the angle of incidence leads to the value of the function falls below that until it is secondary peaks due to the distortion in the image, as a result of the increase in aberration as shown in figure (5).

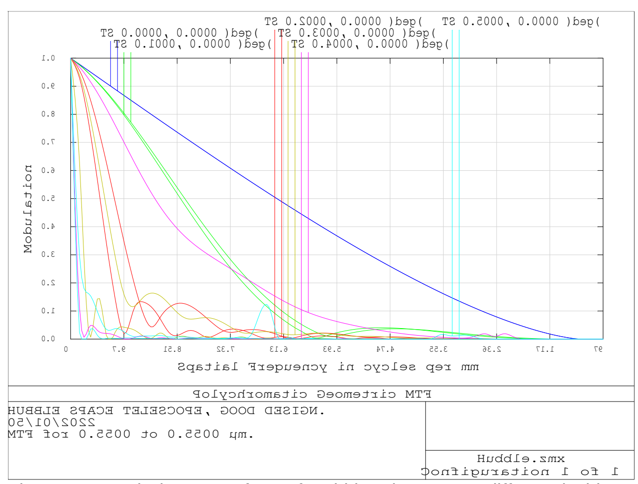

Figure 5: MTF in image surface of Hubble telescope at different incidence angle

PSF shows the distribution of the intensity of the light rays of a point object in the image plane. It is possible to judge the quality of the image through the Strehl criterion, this criterion shows that ideal image has an intensity in the center of the image by (85%). If this percentage is less than the specified standard, the image will be judged as bad. A good image formed according to PSF is limited by diffraction only (aberration free), the diffraction pattern is in the form of a maximum central peak that includes most of the intensity arriving at the image surface.

Figure (6) shows the intensity distribution in the image plane according to PSF for different values of the angle of incidence. The figure shows the two points of the value of the function as the angle of incidence increases to become almost zero. The Strehl criterion varies in value as follows: (1, 0.651, 0.042, 0.011, 0.01, 0.002) When the angle of incidence is gradually increased, as shown in Figure (6). To reach a very low value due to the poor distribution of rays in the image plane. PSF gives an idea of the intensity distribution and thus the sharpness of the image. The sharpness shows the clarity of the image, which shows the ability of the optical system to distinguish between two point objects that are very close together. This is very important in astronomical observation, especially when observing stars or galaxies that are close together.

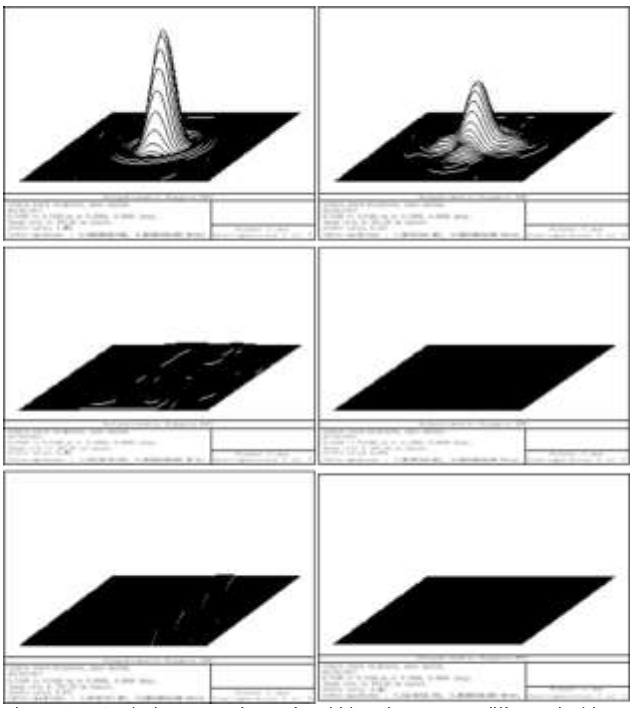
Figure 6: PSF in image surface of Hubble telescope at different incidence angle

CONCLUSION

The imaging optical system needs to align the object with the optical axis to avoid off-axial aberration. The amount of aberration is proportional to the angle of incidence due to the distance of the object from the optical axis. The analysis tools that used in this work showed the quality of the image produced in the telescope due to the use of aspherical mirrors that eliminate spherical aberration, despite the enlargement of the pupil size, and this advantage of the engineering design of the Hubble telescope.

REFERENCES

1. Marc R. Zawislak. "Design Optimization Mode for a Schmidt-Cassegrain Telescope". Optica magazine. 2006. 34. pp:46.
2. V. Yu. Terebizh. "Optimal baffle design in a Cassegrain telescope". Experimental Astronomy, 2001 11:171–191,.
3. Ivan Krastev, "Back to Theory - Ray Tracing by Donald Feder through Aspherical Surfaces – Conic Sections". ATM Letters. 2004. 2, pp: 12
4. Radziemski, L. J. and Cremers, D. A., "Handbook of Laser Induced Breakdown Spectroscopy" , Wiley, West Sussex, 2013. UK, 432
5. De Lucia, F., Harmon, R., Mc Nesby, K., Winkel, R. and Miziolek, A., "Laser-induced breakdown spectroscopy analysis of energetic materials", Appl. Opt. 2003. 42(30), 6148-6152.
6. Ostmark, H., Nordberg, M. and Carlsson, T. E., "Stand-off detection of explosives particles by multispectral imaging Raman spectroscopy", Appl. Opt. 2011. 50(28), 5592-5599.
7. Romano, A. and Cavaliere, R., "Newtonian and Cassegrain Telescopes, Geometric Optics: Theory and Design of Astronomical Optical Systems Using Mathematica", Springer International Publishing, Cham, 2016. 107-118.
8. Mullaney, J., "Reflecting Telescopes, Buyer's and User's Guide to Astronomical Telescopes & Binoculars", Springer London, 2007. 35-45.
9. Schroeder, D. J., "Hubble Telescopes and Cameras, Astronomical Optics", Academic Press, San Diego, 2000. 164-184.
10. Wilson, R. N. "Reflecting telescope optics basic design theory and its historical development". Berlin, Heidelberg, New York, Springer, 2007. 34.
11. Xuan Liua, Junhong Denga, King Fai Li, Mingke Jin, Yutao Tang, Xuecai Zhang, Xing Cheng, Hong Wang, Wei Liu and Guixin Li. "Optical telescope with Cassegrain metasurfaces". De Gruyter. Nanophotonics. 2020 AOP.
12. 12. Bhavsar, K., Eseller, K.E., Prabhu, R. " Design optimization of Cassegrain telescope for remote explosive trace detection" Proceedings of SPIE 2017. Available from: https://doi.org/10.1117/12.2277932
13. Lee D. Feinberg, Bruce Dean, William Hayden, Joseph Howard, Ritva Keski-Kuha. " Space Telescope Design Considerations", Optical Engineering.2012
14. M. Lallo. " Experience with the Hubble space telescope: 20 years of an archetype". Optical engineering 2012 docs downloaded from https://openair.
15. Liu X, Deng J, Li KF, "Optical metasurfaces for designing planar Cassegrain-Schwarzschild objectives". Phys Rev Appl. 2019. 11: 054055.
16. Al-Hamdani, A. H., Rashid, H. G., Hasan, A. B. "Irradiance distribution of image surface in microlens array solar concentrator" ARPN Journal of Engineering and Applied Sciences, 2013. 8(10), pp. 834–840
17. Al-Saadi, T. M.; Hussein, B. H.; Hasan, A. B.; Shehab, A. A.; "Study the structural and optical properties of Cr doped SnO_2 nanoparticles synthesized by sol-gel method". Energy Procedia, 2019. 157. 2. 457–465.
18. Hasan, A. B., Husain, S. A. "Design of Light Trapping Solar Cell System by Using Zemax Program". Journal of Physics. Conference Series. 2018, 1003(1), 012074
19. Spitzer, Lyman Jr., "Report to Project Rand: Astronomical Advantages of an Extra-Terrestrial Observatory", reprinted in NASA SP-2001-4407: Exploring the Unknown Archived 20 January 2017, 1, p. 546.
20. Williams, Robert, "Hubble Deep Field and the Distant Universe". Bristol, UK: IOP Publishing. 2020. pp. 2–9. ISBN 978-0-7503-1756-6.
21. Andersen, Geoff. "The telescope: its history, technology, and future". Princeton University Press. 2007. p. 116. ISBN 978-0-691-12979-2.
22. Okolski, Gabriel. "A Chronology of the Hubble Space Telescope". NASA. . Retrieved 26 April 2008. 32. Pp: 45-60.
23. Harwood, William. "How NASA fixed Hubble's flawed vision - and reputation". CBS News. 2022. 2. Pp.23-34
24. Garner, Rob, "Update on the Hubble Space Telescope Safe Mode". NASA. Archived from the original on 12 October 2018.