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2.5 m Space Station Co-orbiting Coaxial Telescope

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Abstract

The China Space Station Telescope (CSST) is primarily designed for large-scale multi-color imaging and seamless spectroscopic survey, while also accommodating observations with an integral field spectrograph (IFS), multi-channel imaging, direct imaging of exoplanets, and terahertz-band observations. It is scheduled to be launched in about 2 yr. The telescope is equipped with a variety of terminal instruments. It has important scientific missions but limited observation time, so it is suggested to develop a 2.5 m coaxial telescope that will be co-orbiting with the space station. This additional telescope will mainly focus on time-domain surveys and IFS surveys. Its development budget is lower than the current 2 m off-axis telescope, CSST, but it offers superior system performance. Within the limited operational lifespan of the space station, it can significantly enhance the existing survey efficiency. Like the CSST, this telescope will be able to do multi-color imaging survey, and time-domain surveys are also under consideration.

Key words: space vehicles: instruments – telescopes – surveys

1. Introduction

Multi-color imaging surveys and spectroscopic surveys can obtain a large amount of celestial image data and spectral data, which are of the utmost importance for studying the formation and evolution of celestial objects in the universe and lead to more new astronomical discoveries in the current big data era. For a long time, the international astronomical community has made great progress in ground-based survey observations, such as the 2dF Galaxy Redshift Survey in Australia (Lewis et al. 2002), the Sloan Digital Sky Survey (Gunn et al. 2006) and the Dark Energy Spectroscopic Instrument plan in the United States (Doel et al. 2014), as well as the upcoming first light of the Rubin Observatory (Tyson & the LSST Collaboration 2002). These large-scale survey projects have already achieved or are expected to achieve remarkable scientific results in the study of the large-scale structure of the universe, galaxy physics, quasars, and other areas. In 2009, China built the large scientific facility LAMOST (Guo Shoujing Telescope), which first pioneered large-scale (simultaneous observation of thousands of celestial objects) spectroscopic surveys in the international astronomical community (Cui et al. 2012). As of 2024 December, LAMOST has released more than 33 million spectra to domestic astronomers and international partners,[5] enabling China-based astronomy to first become an international hub of seamless spectroscopic surveys, and helping Chinese astronomy maintain a leading position in the world in the fields of Milky Way and stellar research.

In terms of space astronomy, the launch of the Hubble Space Telescope (HST), with its high-resolution imaging capabilities, has greatly advanced in-depth observations of the universe, such as studies on supernova remnants and galaxy formation (Ferguson et al. 2000). The James Webb Space Telescope (JWST), as the successor of the HST, was launched on 2021 December 25. The telescope has a diameter of 6.5 m, an observation wavelength range of 0.6–28.5 μm, and an observation field of view (FOV) of about 0.046 square degrees (Gardner et al. 2006). On 2023 July 1, the European Space Agency's Euclid space telescope was launched. Compared to JWST, its aperture is much smaller, only 1.2 m, but its FOV reaches 0.5 square degrees, about 186 times that of the JWST (Euclid Collaboration 2004). This wide-field design allows Euclid to scan a larger area of the sky in a shorter time, greatly improving the efficiency of observation data collection. Therefore, the main scientific goal of Euclid is to study dark matter and dark energy in the universe through surveys and to map the large-scale structure of the universe.

The Nancy Grace Roman Space Telescope is developed by NASA, scheduled for launch in 2027. With a 2.4 m aperture, the same as the HST, it boasts an FOV 100 times larger than Hubble's. Its 300 megapixel wide-field instrument can cover a larger area of the sky in a single observation, enabling it to conduct large-scale surveys in a shorter time (Akeson et al. 2019). The primary scientific goal of the Roman Telescope is to

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[5] LAMOST: https://www.lamost.org/dr13/.

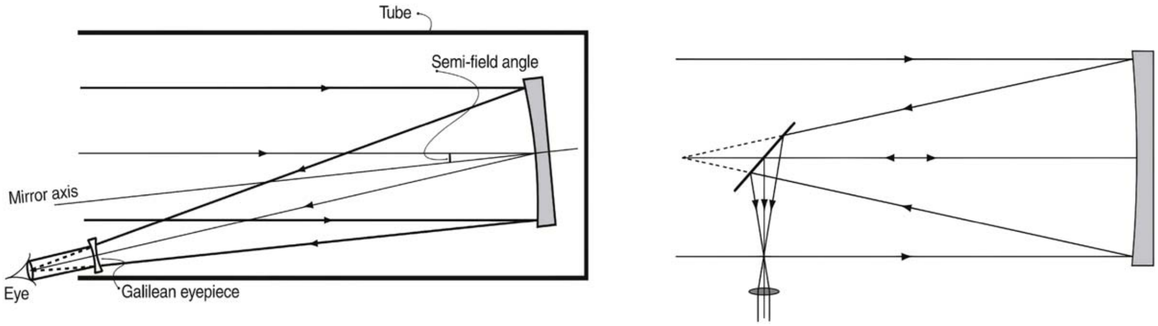

Figure 1. Left: Zucchi's Herschel-type front-view reflecting telescope. Right: The Newton reflecting telescope (Wilson 1996).

study dark energy. By observing the large-scale structure of the universe, such as the distribution and shape of galaxies, and the history of cosmic expansion, the telescope will investigate the nature and evolution of dark energy. Its wide-field instrument will measure light from billions of galaxies to gain a more precise understanding of how dark energy affects cosmic expansion. Additionally, the Roman Telescope will conduct a microlensing survey, expected to discover approximately 2600 exoplanets during its mission.

The China Space Station Telescope (CSST) is a large space-based astronomical telescope planned and constructed as part of China's manned spaceflight project (Zhan 2011). With a 2 m aperture and an FOV of one square degree, it can capture images of approximately 50,000 galaxies and spectral information from over 2000 galaxies, enabling large-scale astronomical surveys and efficient acquisition of a large amount of celestial data. The CSST is equipped with multiple instruments, including a survey module, multi-channel imager, integral field spectrograph (IFS), exoplanet imaging coronagraph, and high-sensitivity terahertz module, with only 60% of the observation time allocated for surveys.

As early as 2013 October 5, Su Dingqiang proposed the scheme of a 2 m telescope co-orbiting with the space station via email to relevant leaders and researchers. The scheme is to use the Tiangong space station as the space port. The telescope usually flies independently in the same orbit with the space station, and the distance between the telescope and the space station is 5–10 km, or even larger. When it needs to be resupplied or repaired and upgraded, it will actively rendezvous and dock with the space station to effectively ensure the normal operation of the telescope in orbit and extend its service life. The co-orbiting scheme outside the cabin of the space station can make the space station not only operate one telescope, greatly improving the scientific ability and operative efficiency. In 2014, Su Dingqiang and Cui Xiangqun published the coaxial scheme of the 2 m space telescope in RAA (Su & Cui 2014). In the first scheme, the telescope is located inside the cabin of the space station, and its characteristics are: (1) the coudé system with relay mirror (SYZ relay mirror); (2) the use of yoke frame, the frame is vibration isolated from the space station to eliminate high-frequency vibration; (3) Two-level system with coarse and accurate control is adopted in the pointing and tracking of the telescope; (4) the rear-end instruments are arranged around the switching mirror, and the instrument switching is completed by the one-dimensional rotation of the module switching mirror; (5) There are two axes: axis I and axis II correspond respectively to the polar axis and the decl. axis in a ground-based equatorial telescope. Axis I points to the pole of the orbit of the space station. This telescope will rotate around axes I and II to track a celestial object and to point to a new celestial object. The second scheme is the co-orbiting scheme. The optical system is basically the same as the first scheme, and the structural layout is slightly different due to the space station envelope constraints.

Although the current 2 m off-axis telescope CSST is primarily focused on multi-color photometric surveys, it also needs to accommodate integral field units (IFUs), spectroscopy, exoplanet imaging, and terahertz-band observations. The scientific tasks of the telescope are important. Therefore, it is suggested to develop another 2.5 m coaxial optical telescope that is co-orbiting with the space station. During the limited lifespan of the space station, another 2.5 m coaxial optical telescope will help to more efficiently and extensively carry out various scientific observations.

2. Coaxial and Off-axis Optical Systems

The characteristic of a coaxial optical system is that the center of the aperture of the optical elements coincides with the optical axis, and with central light being blocked. In an off-axis optical system, the rays of light and the central axis of the optical elements are not on the same straight line, and central light is not blocked.

The development of both coaxial and off-axis telescopes can be traced back to the same era. In 1616, the Herschel-type forward-looking reflector telescope was designed by Zucchi (see Figure 1), which is considered the first appearance of the off-axis telescope. The first Cassegrain-type telescope with tilted parts was the Brachy telescope of Forster and Fritsch in 1876. In 1953, Kurt published a systematic study of an off-axis telescope using two tilted mirrors, called the "Schiefspiegler" telescope. Coaxial telescopes emerged in the same era. Following the invention of the single-mirror Newtonian telescope (see Figure 1), the two-mirror Cassegrain system and the Ritchey–Chrétien system were subsequently developed. The concept of the three-mirror reflective optical system was first proposed by Karl Schwarzschild in 1905, and later various configurations of three-mirror coaxial and off-axis reflective telescopes were developed (also named a three-mirror anastigmat system). The history of the development of telescopes is described in the book "Reflecting Telescope Optics I" (Wilson 1996).

Astronomical optical telescopes basically adopt coaxial optical systems. Looking at the 400 yr development history of astronomical telescopes, classical optical systems are used widely in astronomical telescopes, most of all among coaxial systems, even if the optical and mechanical manufacturing, electronic and thermal control technology, and computer technology have made rapid progress in the past 30 yr. Internationally, more than ten 8–10 m class large astronomical optical telescopes have been built, such as the 10 m KECK (Nelson & Mast 1986), 8.1 m Gemini (Mountain et al. 1994), and 8.2 m VLT ground-based telescopes (ESO 1998), all of which adopt coaxial systems. The 30 m class ground-based telescopes to be built in the future, such as the Thirty Meter Telescope (Sanders 2013), the Extremely Large Telescope (Delabre 2008), and the Giant Magellan Telescope (McCarthy et al. 2016), which all adopt coaxial systems.

For space-based telescopes, the 2.4 m HST (Ferguson et al. 2000) and 3.5 m Herschel infrared telescope (Sein et al. 2003) also use coaxial optical systems. In recent years, several space-based optical telescopes that have been launched or are about to be launched, such as 1.2 m Euclid (Euclid Collaboration 2004), 6.5 m JWST (Gardner et al. 2006), and 2.4 m Roman Telescope (Akeson et al. 2019), have also adopted coaxial or almost coaxial systems. So far, only a few solar telescopes use the off-axis systems, such as the 4 m Daniel K. Inouye Solar Telescope (DKIST; Rimmele et al. 2020) and the 1.7 m telescope at Big Bear Solar Observatory.[6]

In terms of image quality, for the optical systems with the same aperture, focal ratio, and FOV, a coaxial system has better image quality than an off-axis system. Astronomical observations use an area FOV, and the requirement for the designed image quality is mostly close to the diffraction limit throughout the FOV. A coaxial system has the advantages of good symmetry in the spot diagram, simple point-spread function (PSF) shape, and gentle changes within the FOV, which is especially conducive for detecting cosmic dark matter by the weak gravitational lensing method (WL). In telescope projects with WL scientific goals, the scientific requirement analysis documents clearly propose the requirements for the telescope PSF ellipticity, such as the Euclid and JWST (Euclid Collaboration 2004; Gardner et al. 2006).

In terms of the cost and risk of optical fabrication and testing, the asphericity of the primary mirror of an off-axis system is about 2–3 times that of a coaxial system. Especially for an off-axis system with the focal ratio being close to 1, the difficulty of optical fabrication and testing is greater, thereby making the cost and risk of the development of the off-axis system (even if it can be manufactured) much greater than that of a coaxial system with the same aperture size. Taking DKIST as an example, the polishing of the 4 m off-axis primary mirror costs about 11 million US dollars, while the polishing cost of the 4 m primary mirror using the coaxial system is about 4 million US dollars.[7] We think more large aperture space telescopes, such as 4–8 m cases, should also use coaxial optical systems.

3. 2.5 m Coaxial Telescope with Space Station Co-orbiting

The optical system of the proposed 2.5 m space station co-orbiting coaxial telescope is the same as the 2 m coaxial optical system (the optical layouts are illustrated in Figure 2), which was designed by Ms. Genrong Liu in 2010, but the aperture size is increased to 2.5 m or more (depending on launch conditions). The focal ratio is about F/14, and the diameter of FOV is $1\overset{\circ}{.}5$. This system comes from the Chinese 2.16 m telescope's coudé system (such idea was put forward in June of 1972 but published in Su et al. 1990).

The geometric imaging quality of the optical system through the FOV is better than the diffraction limit, i.e., the diameters of spots in which 80% of the enclosed energy is less than $0\overset{\prime\prime}{.}1$, and the energy profile is plotted in Figure 3.

Table 1 shows a comparison of the basic optical performance of the 2 m unobscured off-axis optical system and the 2.5 m coaxial optical system with obscurity, and it can be seen that the light-collecting area and image quality of the 2.5 m coaxial optical system with obscurity are better than those of the 2 m unobscured optical system.

The Modulation Transfer Function (MTF) of different configuration systems is plotted in Figure 4. From the figure, it can be seen that the 2 m unobscured system has a slightly better MTF at medium and low frequencies than the 2.5 and 2.7 m obscured systems. However, in the high-frequency part, which is more emphasized in astronomical observations, the 2.5 and 2.7 m obscured systems are far better than the 2 m unobscured system.

The étendue is a widely used parameter which describes the efficiency of the telescope as a survey tool. The étendue is equal to the telescope's light-gathering area (in m^2) times the FOV (in deg^2). With better angular resolution, higher survey efficiency can be achieved. The sky survey rate is defined such

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[6] BBSO: https://www.bbso.njit.edu/nst_project.html.

[7] DKIST, 2006, Preliminary Design and Final Design Reviews (private communication).

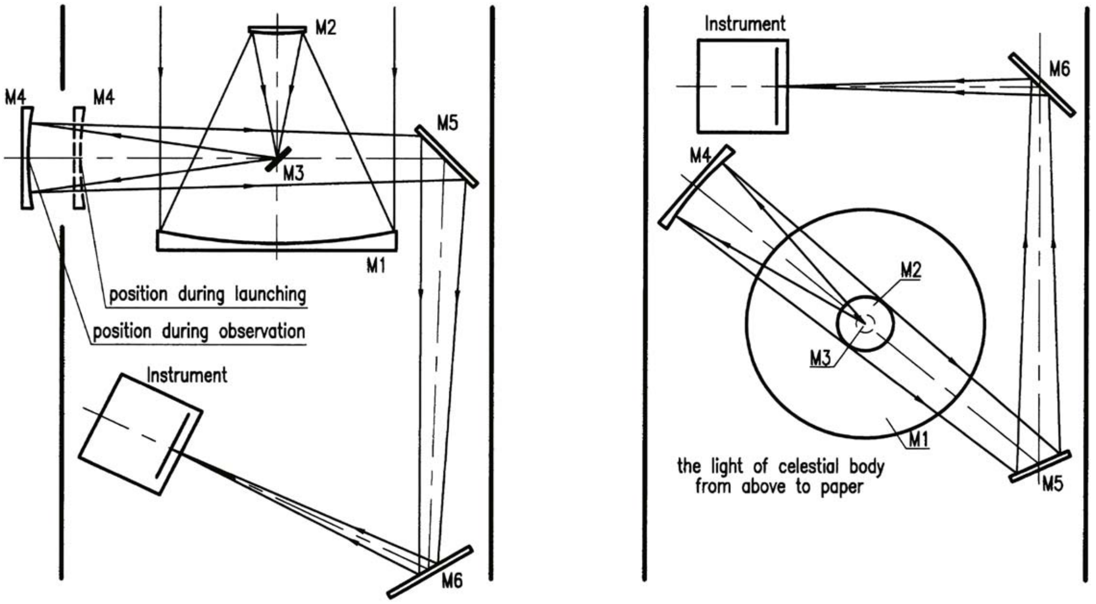

Figure 2. The optical layouts of the 2.5 m coaxial telescope system (Su & Cui 2014).

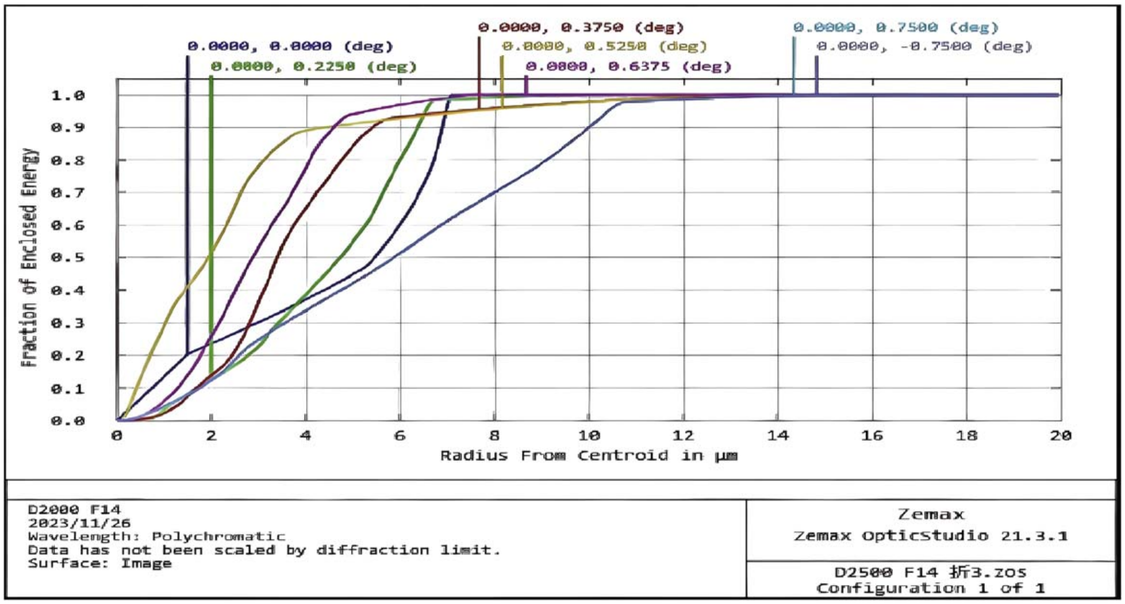

Figure 3. Enclosed energy profile of the optical system of the 2.5 m coaxial telescope.

Table 1
Comparison of the Basic Optical Characteristics of the Two Optical System Configurations

	Obscured Optical System (2.5 m Aperture with a Linear Obscuration Ratio of 0.37 in Figure 2)	Unobstructed Optical System (2 m Aperture)
The light-collecting area	4.24 m^2	3.14 m^2
Diffraction limit	0.″108	0.″125

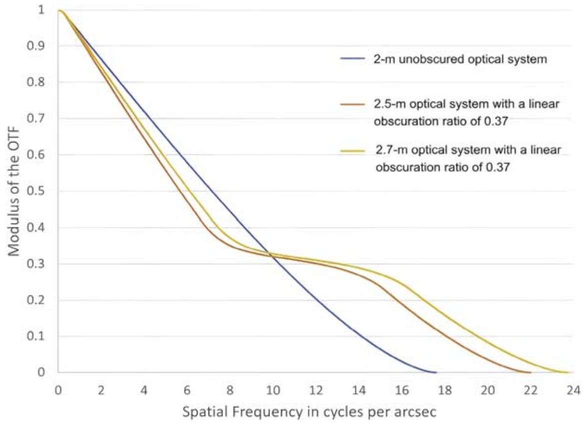

Figure 4. The MTFs of the different configurations.

that the étendue is divided by the angular image sizes squared. Due to atmospheric turbulence, the imaging quality of ground-based telescopes is approximately $1''$ (low to $0\farcs7$ for a good site), while a 2.5 m space telescope can achieve an image quality of about $0\farcs1$. Therefore, although the 2.5 m telescope has a smaller aperture and FOV, its sky survey rate can still be comparable to that of a 6.5 m telescope with a $3\fdg5$ FOV. This 2.5 m telescope will mainly focus on time-domain surveys and IFS surveys, and an extremely low-dispersion spectroscopic survey can be considered.

4. Conclusion

(1) This letter proposes a 2.5 m coaxial telescope that co-orbits with the space station, with an FOV of 1.76 square degrees, which will mainly focus on time-domain surveys and IFS surveys, and an extremely low-dispersion spectroscopic survey can be considered; after the space station ceases operation, it can independently conduct survey observations.

(2) Compared with an off-axis system, the coaxial system can reach higher precision and with lower cost. With the same budget and launch conditions, the cost of a 2.5 m space coaxial telescope is lower (about 1/3-1/2 of the budget) and the development cycle is shorter.

(3) The 2.5 m coaxial telescope has a larger aperture and better optical performance. Compared with the 2 m off-axis system, the 2.5 m coaxial telescope is 1.35 times larger in terms of light-collecting area and 1.16 times smaller in terms of diffraction resolution.

(4) The coaxial secondary mirror and the spider do not have the cross-vane diffraction effect on faint sources, and even if they have an impact on bright sources, it is uniform and can be removed with a program. This can be seen from the observation results of HST and JWST.

(5) It is recommended that an additional 2.5 m coaxial telescope be developed expeditiously. The telescope should be at a certain distance from the existing 2 m CSST.

(6) This additional 2.5 m coaxial telescope would enhance the efficiency of sky surveys considerably, with minimal additional cost required for the duration of the station's operation.

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