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空间引力波探测星载望远镜专题导读

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引力波自 2015 年被直接探测到以来，为人类认识宇宙提供了新的视角[1]。三位美国科学家因在 LIGO 探测器和引力波观测方面的决定性贡献而获得了 2017 年的诺贝尔物理学奖[2]。继地面干涉仪的手段实现高频引力波探测之后，空间引力波探测将是下一阶段的重点发展方向，其大空间尺度可突破地面探测的频段限制从而实现低频引力波探测。目前比较知名的空间引力波探测计划包括欧空局主导的 LISA 计划[3]，我国的“天琴计划” [4-5]和“太极计划” [6] 等。空间引力波探测均采用三星六链路结构设计，其中星载激光干涉仪是引力波探测计划的核心测量仪器，相应的研究成果也比较多，技术进展较快。相对而言，星载望远镜作为激光发射和接收端扩束系统，其性能要求远高于常规光学设备，比如杂散光和光程稳定性等性能指标将直接影响引力波信号探测的信噪比。目前，针对引力波探测星载望远镜相关关键技术的研究还较少。《光电工程》此次组织的“空间引力波探测星载望远镜”专题，围绕空间引力波探测星载望远镜设计与分析、核心指标优化与测试等方面介绍该领域的现状与发展趋势，共收到了来自中山大学“天琴计划”教育部重点实验室、浙江大学、北京理工大学、华中科技大学，以及北京空间机电研究所、中国科学院西安光学精密机械研究所、中国科学院光电技术研究所等高校和科研院所的十多篇相关论文，将分批刊出。

2023 年第 11 期出版的“空间引力波探测星载望远镜专题 (一)”包括 1 篇综述和 7 篇科研论文。论文《空间引力波探测望远镜研究进展》围绕望远镜设计、研制与测试，对星载望远镜的光学系统、光机结构、空间热环境与热控、杂散光仿真与抑制、稳定性测量等方面的研究进展进行了综述[7]。此外，还有 7 篇研究论文，主要围绕星载望远镜光程稳定性、杂散光、波前与指向等核心技术指标的实现，从理论计算、仿真模拟，实验测试等多种途径开展研究，探讨星载望远镜设计与研制的最优解。《引力波探测望远镜超低热变形桁架支撑结构设计技术》通过设计 CFRP 铺层改变材料热胀系数的方法，进而解决了桁架支撑结构热变形问题，同时针对望远镜装调性能的要求，给出了结构的分段式设计方案[8]。《望远镜光程稳定性测量方案设计及噪声理论分析》基于外差干涉测量原理，设计了高共模抑制干涉测量方案，建立了光程噪声理论模型，并根据 1 pm/Hz$^{1/2}$@1 mHz 光程稳定性指标需求，分配测量系统组成部分光程噪声水平[9]。《空间引力波望远镜内部光场计算方法研究》论证了采用基于矢量光线追迹的衍射积分算法建立仿真算法的必要性，基于该算法建立了仿真程序，进行了波前计算精度的验证，并展示了矢量光场仿真计算结果[10]。《基于离轴四反的空间引力波探测激光发射望远镜设计》从传统像平面像差理论和光瞳像差理论出发，建立了望远镜的初始结构，然后利用 Zemax 的宏编程实现了光瞳像差和像平面像差的自动校正，实现了高性能星载望远镜的设计[11]。《基于夏克-哈特曼传感器的星载望远镜波前测量技术研究》提出了一种基于夏克-哈特曼波前传感器原理的星载望远镜波前像差测量方法，该方法采

用经过频域阈值去噪处理后的频域上的互相关算法[12]。《空间引力波探测系统中超光滑光学元件表面散射特性分析》针对超光滑光学元件，建立了一种能快速准确地分析和预测其表面散射特性的非傍轴标量散射模型，并研究了各种因素对不同表面统计分布特征下的角分辨散射分布的影响[13]。《空间引力波望远镜超前瞄准机构致动器电荷驱动位移行为研究》提出等效电容量计算方法定量分析压电致动器在电荷驱动下的位移响应特性，并通过仿真和实验验证了计算方法的准确性和可行性，为空间引力波探测望远镜超前瞄准机构的高精度指向控制提供了可能的分析方法和实现途径[14]。

“空间引力波探测星载望远镜”专题依托国家重点研发计划“引力波探测”2021 年度重点专项“超稳和超高杂散光抑制能力的星载望远镜系统设计研究”、“星载望远镜研制与装调技术研究”以及“超高精度星载望远镜性能测试与评估技术研究”等项目，专题出版的部分论文源自该专项项目的重要学术会议，以及后续依托该会议精神衍生出的研究成果。希望通过该专题对引力波探测星载望远镜相关理论、技术现状和前沿进展的探讨，促进该领域新理论、新技术和新方法的产生与迭代，并逐步发展成熟，为我国空间引力波探测计划提供有效手段和有力支撑，也为广大同行开展相关技术研究、合作交流提供重要参考。

当然，本专题的形成只是一个开始，在理论、方法和技术覆盖面、成熟度与预期目标仍然存在较大差距，我们将持续不懈努力、力臻完善，也期望广大相关领域科研工作者能够为我们提供宝贵意见和发展建议，不胜感激！

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Special issue on telescopes for space gravitational wave detection

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Since gravitational waves were directly detected in 2015, a new perspective was provided for human to explore the universe. In 2017, three American scientists have won the 2017 Nobel Prize in Physics for their outstanding contributions to the LIGO detector and gravitational wave observations. After the realization of high-frequency gravitational wave detection by employing a ground-based interferometer, the space gravitational wave detection will be the focus of the next stage, which can break through the frequency band limitation of ground-based detection because of the large spatial scale, and can realize low-frequency gravitational wave detection. Currently, the well-known space gravitational wave detection programs include the LISA program led by the European Space Agency, China's TianQin program and Taiji program, etc. And these programs all employ the three-satellite and six-link structure, in which the satellite-based laser interferometer is the core measurement instrument of the detection program, and corresponding research results are relatively numerous and the technology is advancing rapidly. Relatively speaking, the telescope, as the laser emission and receiving beam expansion system, have much higher performance requirements than conventional optical equipment, such as stray light and optical path stability, and other performance indicators will directly affect the signal-to-noise ratio of the gravitational wave detection. At present, little research has been done on key technologies of telescopes for space gravitational wave detection. Therefore, the journal of *Opto-Electronic Engineering* organizes the special issue on "Telescopes for space gravitational wave detection", which focuses on the design and analysis, and the optimization and testing of core indicators of the telescopes for space gravitational wave detection, and introduces the current situation and development trend of the field. A total of more than ten relevant papers have been received from the key laboratory of the Ministry of Education of the "TianQin Program" of Sun Yat-sen University, Zhejiang University, Beijing Institute of Technology, Huazhong University of Science and Technology, as well as Beijing Institute of Space Mechanics & Electricity, Xi'an Institute of Optics and Precision Mechanics of CAS, Institute of Optics and Electronics of CAS and other universities and research institutes, and will be published in batches.

The Special issue on "Telescopes for space gravitational wave detection (I)", published in No. 11, 2023, includes one review and seven articles. The paper "Research progress of telescopes for space-based gravitational wave missions" provides an overview of research progress in optical systems, opto-mechanical structures, space thermal environments and thermal control, stray light simulation and suppression, and stability measurements for telescopes. In addition, the other seven research articles explore the optimal solutions for the design and development of telescopes from theoretical calculations, simulations and experimental tests, which mainly focus on the core technical indexes such as optical path stability, stray light, wavefront and pointing of telescopes. In "Design technology of the truss support structure of the ultra-low thermal deformation gravitational wave detection telescope", the problem of thermal deformation for the truss support structure is solved by designing a CFRP layer to change the thermal expansion coefficient of the material. Meanwhile, this paper gives a segmented design plan of the support structure for the requirements of telescope mounting performance. In "Design of optical path stability measurement scheme and theoretical analysis of noise in telescope", a high common mode suppression interferometry program based on heterodyne interferometry is proposed, a theoretical model for the optical path noise is built, and optical path noise levels to the components of the measurement system is assigned according to the 1 pm/Hz$^{1/2}$@1 mHz optical path stability metrics requirements. In "Research on optical field calculation methods in the space gravitational wave telescope", the wavefront calculation simulation program is built utilizing a diffraction integration algorithm based on vector light tracing, and the simulation results of vector optical field are displayed. In "Design theory and method of off-axis four-mirror telescope for space-based gravitational-wave mission", the initial telescope structure is built up based on the traditional focal plane aberration theory and the optical pupil aberration theory, and then the automatic correction of optical pupil aberration and focal plane aberration was realized by employing Zemax macro programming, and finally a high-performance space telescope is designed. In "Research on wavefront measurement technology of space-based telescope using Shack-Hartmann wavefront sensor", the wavefront aberration measurement method for space telescopes based on the Shack-Hartmann wavefront sensor is proposed, which employs a mutual correlation algorithm with threshold denoising processing in the frequency domain. In "Analysis of surface scattering characteristics of ultra-smooth optical components in gravitational wave detection system", a non-equatorial scalar scattering model is built, which can quickly and accurately analyze and predict their surface scattering characteristics for ultra-smooth optical elements, and the effects of various factors on the angularly resolved scattering distributions under different surface statistical distribution characteristics are analyzed. In "Study on the charge driven displacement behavior of the actuator of the point ahead angle mechanism of a space gravitational wave telescope", an equivalent capacitance calculation method is proposed to quantitatively analyze the displacement response characteristics of piezoelectric actuators driven by electric charge, and the accuracy and feasibility of the method is verified experimentally and simulationally, which provides a possible analytical method and implementation approach for the high-precision pointing control of the over-targeting mechanism of the space gravitational wave detection telescope.

The Special issue on "Telescopes for space gravitational wave detection" is supported by numerous programs, including the National Key Research and Development Program "Gravitational wave detection", the 2021 Key Special Program "Design and investigation of the space telescope system with ultra-stable and ultra-high stray light suppression capability", "Investigation of space telescope development and adjustment techniques", and "Investigation of ultra-high-precision space telescope performance testing and evaluation techniques", etc. Some papers published on this issue originated from the major academic conferences of these programs and subsequent research results derived from the spirit of the conferences. We hope that through the discussion of this special issue on the theory and technology status and frontier progress of the telescope for space gravitational wave detection, promoting the generation and iteration of new theories, technologies and methods in this field, and gradually developing and maturing them, meanwhile, also providing effective ways and strong support for China's space gravitational wave detection program, and also providing the important reference for the majority of colleagues to carry out related technical research, cooperation and exchange.

Certainly, this special issue is just a beginning, there are still big gaps in the theory, methodology and technology coverage, and maturity and the expected goal. We will continue to make unremitting efforts to improve, and also hope that the majority of researchers in this field can provide us with valuable advice and development ideas, we would be grateful!