Stray light testing techniques for gravitational wave telescopes

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Gravitational wave telescopes play a crucial role in gravitational wave detection endeavors due to their high detection sensitivity and the requirement to operate within an extremely low-noise environment. When the telescope is in orbit, it will not only be impacted by stray light from external radiation sources but also generate stray light itself, which will interfere with the detection of gravitational wave signals and decrease the detection sensitivity of the telescope. There are two types of relevant stray light testing apparatuses: one is the stray light coefficient measuring instrument, which mainly employs the "black spot method" to assess the overall stray light suppression performance of the optical system; the second is the point source transmittance measuring instrument, which mainly evaluates the stray light suppression capability of the measuring system for the stray light sources outside the field of view with varying incidence angles. However, neither of them can test for the stray light caused by the telescope itself. Currently, the level of stray light in gravitational wave telescopes is primarily based on heterodyne interferometry to test the influence of backward stray light noise on phase measurement for further analysis and evaluation, but the stray light of telescopes has not been directly measured and cannot provide specific and practical guidance for the design and processing of telescopes. In this paper, a set of telescope stray light test system is established to strictly control the environmental stray light, and specific stray light suppression designs are carried out for the stray light introduced by the specific path light, significantly reducing the influence of the system on the external environmental light and thereby enhancing the test accuracy of the system. Through high-precision stray light theoretical modeling, the stray light test capability of the system is better than $1:10^{-8}$. Simultaneously, standard optical mechanical structures with different structural forms are designed, high-precision scattering characteristic models are established, and software theoretical simulation design and system tests are conducted. The results indicate that the logarithm of the ratio between the test results and the analysis results is better than 0.5. The experimental results demonstrate that the system can directly measure the stray light of the telescope and evaluate the design and machining performance of the telescope.

引力波望远镜在引力波探测任务中起到关键的作用，其检测灵敏度高，需要在极低噪声的环境中运行。望远镜在轨运行时不仅会受到外部辐射源的杂散光影响，自身也会引起杂散光，会干扰引力波信号的检测，降低望远镜的探测灵敏度。现有的相关杂散光测试设备主要包括两种：一个是杂散光系数测量仪，主要是采用“黑斑法”对光学系统的整体杂散光抑制性能进行评估；二是点源透过率测量仪，主要是针对不同入射角的视场外杂散光源对测量系统的杂散光抑制能力进行评估。但二者均无法对望远镜自身引起的杂散光进行测试。目前，引力波望远镜杂散光水平主要是基于外差干涉测量的方法测试后向杂散光噪声对于相位测量的影响来进一步分析评估，但并未对望远镜的杂散光进行直接测试，无法对望远镜的设计及加工提出具体的实际指导作用。本文采用建立一套望远镜杂散光测试系统，对环境杂散光进行严格地控制，针对特定路径光线引入的杂散光进行具体的杂散光抑制设计，进行极大地降低了系统受到外部环境光的影响，从而提升了系统的测试精度，通过高精度杂散光理论建模，系统杂散光测试能力的优于$1:10^{-8}$。同时，设计不同结构形式的标准光机结构件，建立高精度散射特性模型，进行软件理论仿真设计及系统测试，结果表明测试结果与分析结果比值的对数优于0.5。经实验验证，此系统可对望远镜杂散光进行直接测试，用于评估望远镜的设计及加工性能。