



The research of wavefront sensor based on focal plane and pupil plane

Xinxue Ma^{*}, Jianli Wang

Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

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ABSTRACT

Large aperture telescope with its high concentrated capability and high resolution plays an important role in many fields. The demand for large aperture imaging telescope is increasingly urgent, there are a lot of challenges with the increase of telescope aperture during the optical processing and testing. In order to solve the above problems, this paper mainly studies wavefront sensing technology which is the key technology in the adaptive optics system, launches a comprehensive in-depth study on the pupil plane wavefront sensor and focal plane wavefront sensor, introduced the pupil wavefront detector and focal plane wavefront detector, and then compares both of them, this work has important implications for theoretical research and engineering applications, providing a favorable guidance for the practical application of adaptive optics system is also needed for the large-diameter telescope distortion and provides a reference wavefront aberration detector.

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1. Introduction

In order to pursue higher resolution observations, whether ground or space-based telescopes [1], a common trend is the increasing diameter of the primary mirror of the telescope. To some extent, the aperture size becomes a reflecting telescope observing capabilities of indicators. However, when light-wave goes through the atmosphere, due to the dynamic perturbation of atmospheric turbulence, the beam quality will be severely damaged, which will cause the wavefront distortion. For large-aperture ground telescope imaging system, atmospheric turbulence makes the target image blur, light scatter, resolution in serious decline. On the other hand, increasing the size of the primary mirror to the telescope design, processing, manufacturing, testing and other technology has brought unprecedented challenges. Therefore, it needs adaptive optics (AO) [2] caused by atmospheric turbulence correction, which is an important prerequisite for achieving effectively detect wavefront distortion and correction [3]. Development of wavefront sensor (WFS) [4–7] becomes one of the key issues for AO system. To solve the above problem, this paper mainly studies WFS technology which is the key technology in the adaptive optics system, launches a comprehensive in-depth study on the pupil plane wavefront sensor (PP-WFS) and focal plane wavefront sensor (FP-WFS), first introduces PP-WFS and FP-WFS, and then compares both of them. This work has important implications for theoretical research

and engineering applications, providing a favorable guidance for the practical application of AO system is also needed for the large-diameter telescope distortion and provides a reference wavefront aberration detector.

This paper is organized as follows: the introduction of WFS is presented in Section 2, the comparison of PP-WFS and FP-WFS in Section 3 and the summary in Section 4.

2. Wavefront sensor

According to the position in which the optical system, wavefront sensor can be divided into pupil plane wavefront sensor and focal plane wavefront sensor in the exit pupil position of the optical system.

2.1. Pupil plane wavefront sensor

The common PP-WFS has knife-edge instrument, Shack–Hartmann sensor and interferometers and so on.

2.1.1. Knife-edge instrument

The knife-edge instrument is a shadow method using the principle of a simple tool to check the wavefront error of optical components in the processing of the scene. The principle is that light emits from the light source via the first condenser lens converging planar light-wave, and then goes through the second condenser lens through an aggregation of small plane mirror steering, imaging in the vicinity of the light source edge. Shown in Fig. 1, put a pinhole in the image of the light source, and then get the

* Corresponding author. Tel.: +86 0431 86708071.

E-mail address: xinxuema@hotmail.com (X. Ma).

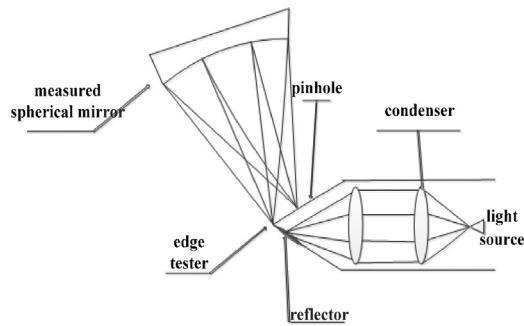


Fig. 1. Schematic of knife-edge instrument.

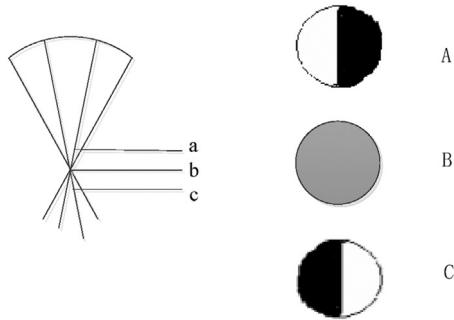


Fig. 2. The theory of knife-edge instrument measurement.

standard point source. The spherical wave outgoes from pinhole exposure to the detected spherical mirror, after spherical reflector, and then images onto the blade. With a knife cut a pinhole image, we can see the situation of the shadow which is not far from the measured spherical mirror after the edge; we will know the error of the measured spherical mirror.

We can see from Fig. 2, the convergence of the light from the mirror, the blade moves to a (former Focus) at the cut, this time to see the light on the right side of the first mirror is blocked. See the mirror from Fig. 2A. If c (back focus) is at the cut with a knife, then the mirror to the left of the first light is blocked, you can see the mirror as shown in Fig. 2C. If b (focus on) at the cut, then all the light on the mirror surface are obscured edge, mirror should suddenly dimmed, but there is always a certain size pinhole instead of infinitely small, due to the volatility of the principle of light (needle infinitesimally small hole), the smallest image of the pinhole is a diffraction spot, so we see the mirror is darkening, then cut into the most sensitive area, as shown in Fig. 2B.

2.1.2. Shack–Hartmann WFS

Shack–Hartmann (S-H) WFS [8–9] is an instrument that can be used to detect the wavefront in the processing site of the reign of detection, which is based on the slope of the wavefront measurement. In the detection time, using compensation glass and the microlens array, which is difficult to manufacture, needs high precision, and due to restrictions by the lens array, it has a lower lateral resolution.

The principle of S-H WFS is to use a microlens array at the aperture plane of the incident wavefront spatially sampled, the corresponding target image formed at the focal plane of each sub-lens, as shown in Fig. 3, the pore size and the focal length of the same set of micro-lens make the main microlens aperture of the detector divide into several sub-aperture, the distortion of the wave are imaged at the focal plane of each micro-lens, use an area array detector member (such as a CCD camera) measure the offset (wave-front slope) of each sub-aperture point and the calibration position,

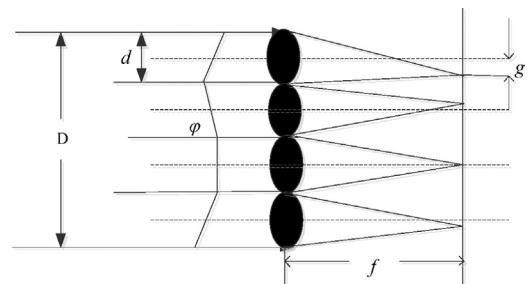


Fig. 3. Schematic of the theory of S-HWFS.

and then use wavefront restoration algorithm indirectly measure the size of the distortion of the wavefront.

2.1.3. Interferometer

Interferometer has high measurement accuracy, a high sampling rate; the order of the wavelength detection sensitivity can be achieved to the order of wavelength. First, we compare with interferometer and the former standard wavefront, and then obtain the measured data of the wavefront aberration by comparing, due to higher requirements of the environmental factors, the vibration and air turbulence is sensitive, and so in general, it needs work at a constant temperature of indoor environment. According to the reference wave generation method is divided into: point diffraction interferometer and shearing interferometer [10,11].

R.N. Smartt first proposed point diffraction interferometer in 1972, the principle is to focus the beam to be detected in a translucent panel with a pinhole mask; we can get the phase contour map of the detected wavefront with the spherical reference wave produced by the pinhole diffracted and the interference pattern detected by the mask resulting wavefront.

Shearing interferometer splits the wavefront through the detected device into two plane waves by using a suitable optical system, and make them mutually staggered (shearing) from each other, they have a two-wave interference pattern in the overlap portion surface, get wavefront information by analyzing interference striped. The advantage is relatively simple and stable structure, strong anti-jamming capability and eliminates the need for a standard reference optical surface; the disadvantage is more difficult to interpret the interference pattern formed after the cut, lower solar energy utilization. Thus, it is replaced by a subsequent interferometer.

Wave-plane interferometer is a precision instrument that detects surface shape of the optical element, the wavefront aberration of the optical lens, the optical uniformity of the material and so on. It has high detection accuracy, measurement accuracy is generally 1/10 wavelength to 1/100 wavelength, but difficult to detect the surface shape in the processing scene.

2.2. Focal plane wavefront sensor

FP-WFS is in the image plane of the imaging optical system position, often do not need to add the auxiliary optical components, which capture the multi-frame short-exposure image by given the defocus aberration, the solver to get the wavefront phase information of the optical system and can use Zernike polynomials fitting the individual aberrations. The most common application FP-WFS is phase retrieval (PR) WS, phase diversity (PD) WS, phase-diversity phase retrieval (PDPR) WS, extend Nijboer–Zernike (ENZ) WS.

2.2.1. IPR-WFS

PR technique [12–16] uses light field diffraction model, diffracted calculate the assumed input light field and obtain the intensity distribution of the output surface of the light field.

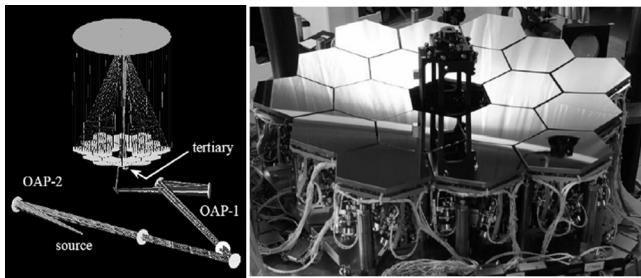


Fig. 4. Meter-class telescope splicing test platform.

Comparing to field intensity data and the calculated intensity true phase output surface of the light field generated both the minimum error as a criterion; find the best match the phase distribution of the real field data by iterative search. PR algorithm has become a very important research area, mainly due to PR algorithm has applications in signal recovery, the design of the optical diffraction element and so on. Because based on diffraction theory, relative to the measurement methods based on the interferometric, this method has simple structure, low cost, and not susceptible to interference inherent vibration and environmental characteristics, very suitable for the measurement of large optical components.

Being developed by NASA – Jet Propulsion Laboratory in exploring the next generation space telescope splicing – The James Webb Space Telescope (JWST) [17,18] is using the PR technique. Primary mirror diameter is 6.5 m, using 18 hexagonal sub mirror mosaic with each diameter of 1.3 m, optical design and manufacturing tolerances within range to achieve diffraction-limited performance. Comprehensive every technical, JWST commissioning and periodic maintenance method based on optical wavefront sensing image information and control systems to align the position of each sub-mirror to reduce the impact caused by the shape error. The wavefront sensing technique is based on image information by the image acquisition star point light source, through the iterative processing to recover the optical phase information. To verify the effect of PR technology, ensuring JWST telescope in the space expanded to meet the design requirements, in addition to, a meter-class telescope splicing test platform built. As shown in Fig. 4.

The Hubble Space Telescope (HST) [19,20] shortly after launch, the researchers found that there is a serious aberration of the optical system. If the size can be detected and the reason that aberration can be found, which will play three major roles for the imaging telescope, first of all, we can resort to correcting aberrations, secondly, to learn how to align the secondary mirror of the telescope to reduce astigmatism and coma, in addition, the calculation and analysis point spread function (PSF) of the system for clarity telescope collected degraded image. The method of diagnostic aberrations of the optical system is based on PR technology, obtain wavefront phase information of the optical system by continuous acquisition of different stellar image defocus amount, fitting the individual aberrations, comparing to the design simulation, there is serious spherical aberration in telescope, which is one of successful application of PR in the optical diagnosis.

2.2.2. PD-WFS

PD technology [21,22] was first presented by Gonsalves in 1979, and the core idea is the simultaneous acquisition of two images in the focal plane of the imaging system and the defocal plane of the imaging system, solve the phase distribution of the wavefront and restore the target on the premise of known defocus amount. PD theory was further improved by Paxman, etc. The mathematical model in case of multi-frame PD Gaussian noise and Poisson noise greatly improved the PD estimation accuracy in noisy situations. Vogel and other using of the inverse problem proposed

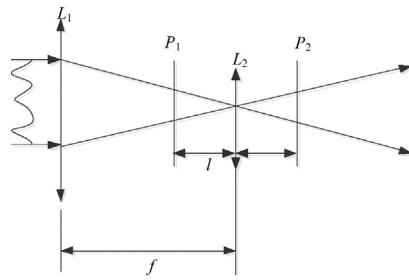


Fig. 5. Schematic of the Curvature WFS.

fast numerical solution. Löfdahl et al. apply Phase-Diversity Speckle (PDS) theory successfully into solar observation areas, access high-resolution images of the sun surface tissue. Bolcar introduced the PD theory to detect synthetic aperture lens and segmentedlens. America Air Force carried out a lot of funding to PD, in Lahaina, Hawaii Air Force Base, the University of Hawaii Maui combining with High Performance Computing Center did observation experiments on space target of 1.6 m telescope during the daytime with PD.

2.2.3. PDPR-WFS

For extended unknown object, we should use PDPR technique [23]. PDPR is to give the optical system one or several known phase diversity (aberration), if the image plane defocus know (we will know defocus aberration). According to the known PDPR, considering the image both of in the focal plane and in the defocus plane, we can restore the aberration of the optical system. Using this method, restore the phase to the extension of unknown objects, we can obtain a clear picture eliminated blur. Löfdahl et al. make PDPR method apply to detect Keck II relative displacement of each block of the primary mirror telescope mirrors. PDPR has been used as precision phase detection of JWST.

2.2.4. Curvature WFS

Roddier first proposed curvature WFS in 1988, makes construction of cheap fast closed-loop of AO system to be possibility. Curvature WFS is to use intensity distribution from the defocus plane to obtain wavefront curvature and phase distribution. The signal of curvature WFS can be directly used to control a deformable mirror, but curvature WFS only use for lower order aberrations mode, its measurement accuracy is low for high order aberrations, which limits its application.

P1 and P2 on both sides of the focal plane are in the defocus amount with l as the two planes of symmetry, as shown in Fig. 5. The focal length of the lens L1 is twice the focal length of the lens L2. According to the theory of Fourier optics, we can use the Poisson equation to express the relationship of the two corresponding points from the normalized intensity distribution, the curvature of the incident wavefront and the perpendicularity slop of the pupil edge of wavefront. We can find the phase distribution of the incident wavefront by solving the Poisson equation. University of Hawaii uses a curvature WFS develop Hokupa “a astronomical AO system, as shown in Fig. 6.

2.2.5. Pyramid WFS

Pyramid WFS was first proposed by R. Ragazzoni in 1996, with the characteristic of slope sensor and direct phase sensor, which consists of a quadrangular pyramid mirror, relay lens and CCD camera, shown in Fig. 7. Pyramid mirror is a refracting prism, whose bottom surface is similar to the square pyramid, the apex of the prism coincides with the focus of the optical system axis of the telescope, behind the prism is placed the relay lens and CCD cameras in sequence. After the incident wave going through the entrance



Fig. 6. Hokupa "a".

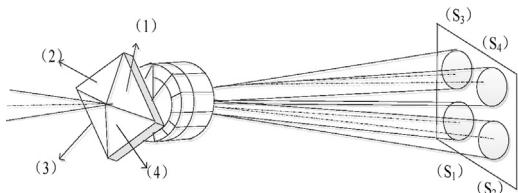


Fig. 7. Pyramid WFS.

pupil of the telescope, converges to pyramid apex, then the four exit pupil is formed on the photosensitive surface of the CCD camera after refracting through the prism of the four facets and a relay lens, followed credited to 1, 2, 3, 4.

Using pyramid mirror can detect error signal of an optical path difference (OPD). The method is to make quadrangular pyramid mirror vertex and a composite focal of the two sub-aperture telescope overlap, simultaneously each obtain two sub-aperture images on each quadrant of CCD, as shown in Fig. 8.

2.2.6. ENZ-WFS

Currently ENZ-WFS was studied in theoretically, which can be used to solve phase, but it has not been applied to practice, so here is a brief introduction. During 1930–1940 years, Zernike invented the diffraction theory, loop polynomial and phase contrast microscopy.

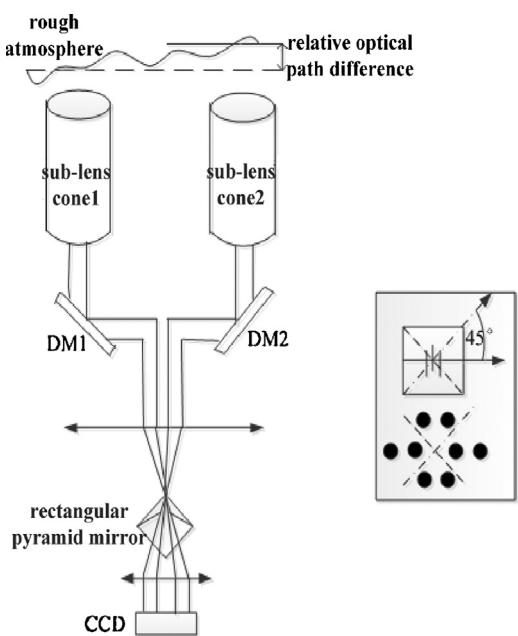


Fig. 8. Detection OPD with pyramid WFS.

His students Nijboer described a complex field with polynomial in the pupil plane and defocus plane in his papers. But because of the limitation of the scalar diffraction theory, the view of Nijboer has not been recognized. Until 2002, Joseph JM Braat, Peter Dirkse, Sven van Haver and Augustus JEM proposed extended Zernike diffraction theory [24,25], which has been widely used in the optical area.

ENZ described the point spread function with the Zernike polynomial coefficients, which makes the aberration of the converse solution become a relatively simple task. Comparing to NZ, ENZ can handle with the larger aberration, and therefore, an analytic equation can describe the amplitude and intensity on the specified location in the different focal plane. For the intensity distribution of cross-section of a shaft, radial and azimuthal, the ENZ equation can be used to obtain an accurate expression. It is an advantage when it comes to the calculating amount. When it comes to other pure numerical techniques of diffraction theory such as Fourier transform method, we can put the numerical analysis results generated by ENZ as a benchmark. ENZ has high precision in mathematics description of the relationship between object and image of the optical system with the large numerical aperture.

3. Comparison of PP-WFS and FP-WFS

Based on the image information of the focal plane wavefront solver system (FP-WFS) has some irreplaceable advantages comparing with PP-WFS. System consists of a spherical point light source, a measured optical system, an image acquisition system (spectroscopic, CCD camera and translation stage), phase retrieval software and signal processing systems. The accuracy of system can reach 1/100 wavelength, dynamic range PV can get to 100 wavelengths. Compared with interferometer, FP-WFS can overcome the effects of vibration and environmental disturbances on the image, to meet different testing environments and vibration conditions; compared with Hartman, FP-WFS can be calculated high-frequency components of aberration that Hartman detector cannot obtain, and can get a good measurement results which must be obtained by Hartman with a few pixels of a number of CCD detector.

3.1. Large aspheric mirror online detection

In general, a large mirror processing including roughing and finishing, finishing stage occupies the main time of the entire processing. In order to ensure accuracy, we need frequently use of a laser interferometer to detect, need to spend a lot of time in the detection. Secondly, the detection of a large mirror needs to be removed from the work piece, for large mirror, the bulky, quality, handling difficulties, but also need to use another tape or other detection tooling in horizontal optical detection, at this time, a large mirror processing and testing status are inconsistent, which caused some difficulty to enhance the machining accuracy. Online detection of the large mirror shape means without removing the work piece, processing in station upper and in the same time detecting. The use of point light source and the spatial light modulator to produce the desired spherical wave, and incident on the measured mirror surface, the camera receives the image point formed by converging light rays, through the continuous acquisition points of the image of a known different defocus amount, use PR algorithm to get the changes between the measured mirror and the ideal spherical wave, according to the relationship of the reference spherical and a spherical geometry, we can obtain aberrations of the aspheric mirror. Schematic of detection is shown in Fig. 9. Imaging captured [26–28] device includes a translation stage and a CCD camera. Online detection can overcome the shortcomings of

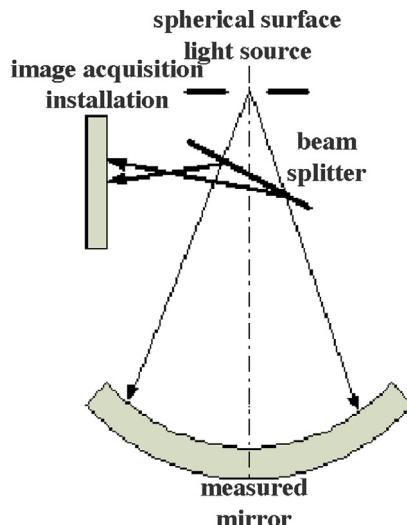


Fig. 9. Schematic of detection with aspheric mirror.

traditional detection, and can achieve a vertical detection, flexible detection, easy to use.

3.2. Optical system online detection

Using FP-WFS method for detection the static aberration of the optical system [29,30] is very simple. Similar with detection mirror, the use of point light source and the spatial light modulator to produce the desired spherical wave being placed in the object position of the collimator, detect the entire system aberration of the optical system from the primary mirror to the CCD detector. The advantage of this method is that in the case of no need change the optical path of the optical system, an accurate measurement can be obtained to the entire system and the transform function. FP-WFS has a good prospect, space optical system can also be implemented in orbit motion detection, using an optical system comes with a CCD camera system to evaluate and diagnose aberration when collecting stars as a target source.

3.3. Sub-mirror mosaic position detection

In recent years, monolithic primary mirror is close to the limit of the size and weight, which is the obstacles to increase light collection efficiency and imaging resolution, people prefer to put the telescope aperture system designed to sub-mirror system. Such systems are in service or under construction include the Multiple-Mirror Telescope (MMT), Keck Telescope, the Very Large Telescope (VLT), and the National New Technology Telescope (NNTT). With respect to large enough to achieve the equivalent resolution monolithic primary mirror telescope, sub-mirror telescope in achieving resolution splicing is very promising and can avoid the creation difficulties in manufacturing a single mirror. In order to achieve maximum resolution, each sub-mirror must be aligned in small fractional wavelengths. So, although requirements in the mirror manufacturing reduced under the concept of sub-mirror, it brings a mosaic mirror each alignment problems. Active methods typically using a laser interferometer detects the interference light of the adjacent segmented mirror, but this method requires a lot of additional sub-mirror misalignment that is not affected by the optical hardware, using Hartmann detector has the same drawbacks. In addition, Hartmann will reduce the sensitivity of the detector or even failure when imaged target extending enough. Using PR and PD technology, we can measure the alignment error of sub-mirror

by the changes of the image, and complete sub-mirror confocal microscopy and total phase.

3.4. Wavefront sensing

The traditional method of WFS is the use of shack Hartmann wavefront, which by measuring the wavefront tilt and reconstruct the wavefront to get the wavefront information. Usually consists of a high speed camera and a microlens array, microlenses measurement accuracy is limited by precision machining and wavefront measurement error. In addition, the use of micro-lens, the target energy is reduced, the SNR drops, and the practical appellation has limitations. Using FP-WFS can get wavefront information of the optical system, according to the need to restore image and the adaptive correction compatible with the adaptive optics system, residual correction because of adaptive systems lag and limitations of the high frequency to detect aberrations, which can significantly improve image quality.

3.5. High-resolution imaging

Optical imaging system is affected by the static aberrations and dynamic disturbances aberration, usually cannot achieve the ideal diffraction limit capacity. General ground-based telescopes to improve imaging resolution methods are adaptive, lucky imaging, blind deconvolution, speckle imaging and so on. Using FP-WFS method can dynamically obtain the wavefront information of systems, and also solves the ideal image of the desired target, to achieve the blurred image clarity. When SNR is strong enough, the camera sampling spatial frequency is high enough, target details rich and enough, even super-resolution imaging can be done.

4. Conclusions

In summary, FP-WFS technology can be widely used in large-caliber foundation optical equipment, space telescopes, binoculars stitching, wavefront detection, image restoration and other areas. In order to improve the testing conditions of the large-aperture optical systems, meet different testing conditions and the requirements of the system, this paper mainly studies WFS technology which is the key technology in the AO system, launches a comprehensive in-depth study on PP-WFS and FP-WFS, this work has important implications for theoretical research and engineering applications, providing a favorable guidance for the practical application of AO system is also needed for the large-diameter telescope distortion and provides a reference wavefront aberration detector.

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