Improvement of telescope resolution using a diffractive phase modulator

Yuxiang Wen, Kunpeng Wang & Dengfeng Kuang

Metasurface, fluorescent microscopy and scanning near-field optical microscopy can improve the resolution of microscopes remarkably, while the resolution of the telescope remains unimproved constrained by its giant objective lenses and distant targets. Here we put forward a way to raise the resolution of telescopes simply by adding a binary optical thin surface around its focal plane. Simulation results show that the surface can raise the image quality in the Cassegrain and Kepler telescope. By nano-lathe, we fabricated a designed binary surface and experiment it in the Kepler telescope. The results are consistent with those of simulation results. More details of the calibrated target are resolvable on the image plane after applying the binary optical surface. It proves that the binary optic surface can make contribute to the resolution of the telescope, thus is beneficial in astronomy, military surveillance field.

Telescope is one of the most important optical instruments and it can be used in a variety of fields such as photography, scouting and space exploration. Since the invention of the telescope in the 17th century, people have made great efforts to improve the performance of the telescope. Achromatic lens and parabolic mirrors are introduced to telescopes to reduce the spherical and chromatic aberrations. However, the diffraction of light limits the minimum resolution in the forms of the Rayleigh criterion as $1.22\frac{\lambda}{D}$, where $\lambda$ denotes the incident wavelength and $D$ refers to the diameter of the objective aperture. Increasing the diameter of the objective lens becomes an obvious way to increase the resolution, China has built a 500-meter aperture spherical telescope to explore the deep space. Aperture-synthesis technique is an alternative way to enlarge the aperture diameter. The Very Large Array (VLA) in New Mexico of America comprises twenty-seven 25-meter radio telescope. Adaptive optics, Fourier telecopy and low-noise antenna are adopted to improve the signal-noise ratio (SNR) at different signal wavelengths. As the aperture becomes larger and the standard of the receiver becomes higher, the complicity and cost of a telescope skyrocket as well.

To cross the diffraction limit barrier and enhance the image quality, researchers presented super-oscillation technique, fluorescent image microscope and evanescent wave detection microscopy using different kinds of probes. The super-oscillation lens trades the light intensity with higher resolution. In 2009, Fumin Huang reached 0.61 diffraction limit by using a purposely-designed mask. The evanescent wave mainly contributes to the image in two distinct ways, scans the evanescent wave like scanning near-field optical microscopy (SNOM) and using negative refractive index material to guide the evanescent wave such as super lens. When the incident light is 600 nm, stimulated emission depletion microscopy (STED) has reached 20 nm resolution and structured illumination (SIM) is able to discover 120 nm particle in its field of views and stochastic optical reconstruction microscopy (STORM) or photoactivated localization microscopy (PALM) are able to distinguish particles with a 30 nm gap. However, these super resolution methods mentioned above are difficult to apply to telescope because the fact that the light signal of a distant object is too faint to bear the loss of super oscillation lens and the aperture of the lens is excessively huge for a subwavelength structure in the metamaterial lens or super lens. In addition, the distant target is unlikely to dye with fluorochrome. Nevertheless, improving the resolution of the telescope is still a priority demand of distant target detection.

Diffractive optics has distinct dispersion character in contrast with traditional lens. Moreover, multiple freedom degrees of the sag provide diffractive optical element (DOE) with strong ability to correct the aberration of an optical system. Researchers have validated its on-axis and off-axis wavefront control ability in membrane.

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Mirrors.基于这一考虑，衍射光学元件已被广泛用于光学图像系统中。Ball Aerospace and Technologies Corp演示了一个大型透射式光学元件。DOE带来新的机会，以轻量化、低成本和更容易的制造表面凹凸。此外，实验证明了DOE强大的像差校正能力。然而，在许多场景中，光学系统仍由传统透镜或反射镜组成，不改变透镜或目标预处理的情况下提高这些望远镜的分辨率具有重要意义。为了减轻重量和提高图像质量，我们提出了一种方法来增加望远镜的分辨率，而不调整光学系统。我们将在望远镜的焦平面添加一个衍射光学元件来调制波前并校正像差。仿真和实验显示，我们设计的DOE可以贡献到我们所用的望远镜的分辨率。

**Results**

**Simulation of DOE in reflective telescope.** 望远镜具有多个透镜在焦平面中。Smyth镜片或Barlow镜片。这些透镜用于场平坦化和像差校正。Freeform透镜设计用于提高望远镜分辨率。然而，这些透镜是厚的，重量大，而且自由形透镜的表面形状很难在高次非线性项的曲率方程中制造。薄光学元件是薄的、轻的，以其强大的波前弯曲和同质化光束。所有的特性使得DOE成为一种合适的元件。反射望远镜是常见的天文望远镜，我们使用一个卡塞格林望远镜模型作为系统的初始结构。为了优化系统，第一镜片的半径为−1200 mm，离心率为−1.038。第二镜片的半径为−394.737 mm，离心率为−3.004。我们设计的DOE可以提高我们所用的望远镜的分辨率。

![Figure 1](https://example.com/fig1.png)

**Figure 1.** The performance of DOE in an optimized Cassegrain telescope (a) Schematic view of the telescope, there are two reflective mirrors (M1 and M2) as the objective lenses, two achromatic lenses (L1 and L2) and a Smyth lens (L3) as the eyepieces of the telescope. (b) The MTF and the spot diagram of the system. The content on the upper-right box is the legend of the MTF curves, the dash lines represents the MTF curves after applying the DOE. Red, green and blue represent three wavelengths of 486 nm, 587 nm and 656 nm in the upper-right spot diagram respectively and ⋇ means the effect after applying the DOE. (c) The cross section of the surface sag of the DOE in this system.
The spot radius of the central field of view (FOV) reaches 1.4 μm and the Seidel coefficients of the system (S1, S2, S3, S4) are all below 10^{-3}, the spot radius and the modulate transfer function (MTF) of the system are shown in Fig. 1(b).

Figure 1(a) shows the simulated optical path of the reflective telescope, the incident light angle magnified by objective lens (M1 and M2) passes through two lenses (L1 and L2) to modify the spherical, coma and astigmatic aberration. Near the image plane, a 3-mm-thick lens is used to flatten the field and correct the distortion and curvature aberration caused by the former system. Seidel aberration coefficients of at the image plane are 0.000396(S1), 0.000104(S2), −0.000014(S3), 0.000235 (S4) and −0.014364(S5). The MTF curves are presented in Fig. 1(b) as the straight line and the spot diagram is shown in the first row of spot diagram at the top of Fig. 1(b). The resolution of the system is good enough for practical detection. To test the performance of the DOE, we replace L3 with a 0.1 mm-thick DOE. The surface sage of the binary element we use are:

\[
Z(r) = \frac{M\lambda}{2\pi(n - 1)} \left[ \sum_{i=1}^{N} A_i \rho^{2i} \text{mod} 2\pi \right]
\]

where \(Z\) is the height of the sag, \(r\) is the radius of the sag, \(\lambda\) is the wavelength of the incident light, \(n\) is the refractive index, \(M\) is the diffraction order, \(N\) is the number of the terms, \(\rho\) is the normalized radial aperture coordinate and \(A_i\) is the coefficient on the \(i\)th polynomial term, mod means modulo operation. In this simulation, \(M \) equals to 1, \(\lambda \) equals to 550 nm, \(N \) equals to 2, \(n \) equals to 1.49 and \(A_1 \) equals to −390.993, \(A_2 \) equals to 118.548 with the normalized radius \(\rho \) equals to 17.397 mm. The sag of the DOE is shown in Fig. 1(c). As we can see in this picture, the MTF curves of the original system approximate the diffraction limit when the field angle approaches 0°. While after we apply the DOE in this system, the MTF curves rises in all FOVs, and the increase is extremely obvious in off-axis field angles. The red dashed line in Fig. 1(b) is apparently higher than the straight red line. From the spot diagram on the upper part of Fig. 1(b), we can also see that the original system is optimized to a good level, and the DOE shrink the spot diagram and reduce the chromatic aberration in a further step, the spot radius of ≈0.5° is smaller than that of 0.5°. Seidel coefficients of the system with DOE are 0.000331(S1), 0.000015(S2), −0.000082(S3), 0.000052 (S4) and −0.014528(S5), the spherical aberration, coma and field curvature are sharply decreased.

**DOE in Kepler telescope.** Simulation. We also check the performance of the DOE in a simple Kepler telescope as a proof-of-principle experiment. The DOE is given as aberration compensation element in the focal plane of the telescope. The system layout shows in Fig. 2.

The incident light (532 nm) passes through the micro-objective and the pinhole to become a point light source, and then a lens is served as a collimator to generate parallel light. The parallel beam lighting in the telescope across a calibration target. We use two plano-convex lenses as the objective and the eyepiece of the telescope, and a DOE is set in the focal plane of the telescope to calibrate the wave front. Finally, a CCD capture the emerging light. The radius of the objective lens is 156 mm with a diameter of 76.2 mm and the radius of the eyepiece lens is 31 mm with a diameter of 30 mm, the material of the lenses are both BK7 and the angular magnification rate of this system is 5. Due to the dispersion and the stray light of the system, the geometric spot radius of the simulated system is 8 mm when the diameter of the entrance pupil is 68.58 mm, moreover the MTF curves is extremely low as shown in Fig. 3(b). When we add a DOE lens in the focal plane, the geometric spot radius is shrink to 0.174 mm with the same entrance pupil, and the MTF curves is much more closer to the diffraction limitation [Fig. 3]. The S1 of the Seidel coefficients drops from 0.184 to 0.163. The sag equation is the same as we used in the Cassegrain telescope, while \(\lambda \) equals to 532 nm, \(\rho \) equals to 3.574 mm.

Fabrication and experiments. For fabrication convenience, we choose \(N \) equals to 2 and \(A_1 \) equals to −349.179, \(A_2 \) equals to 396.199, indicating that the highest order of the sag is four. The sag of the DOE is shown in Fig. 4(a).
The sag surface comprises two parts, in the middle of the DOE is a convex sag and the side of the DOE has a concave shape. The change of the sag is adapted to the on axis and off axis aberration in this system. Considering the difficulty of fabrication, we choose PMMA as the material of DOE. The incident wavelength is 632.8 nm and the refractive index of the PMMA in the wavelength is 1.49. The thickness of the surface is 1.09 μm. We use nanolathe

Figure 3. (a) The spot diagram of the system before (left) and after (right) applying the DOE. (b) The MTF of the system, the blue line is the MTF of the diffraction of the system; yellow dash line and red line are the MTF with and without the DOE.

Figure 4. (a) The cross section of the surface sag of the DOE. (b) is the practice picture of the DOE composed of PMMA. (c) is the image of the DOE in an inverted microscope. (d) is the measurement result of the center sag of the DOE using a surface profiler (the width of the grid is 100 μm and the height of the grid is 100 nm).

The sag surface comprises two parts, in the middle of the DOE is a convex sag and the side of the DOE has a concave shape. The change of the sag is adapted to the on axis and off axis aberration in this system. Considering the difficulty of fabrication, we choose PMMA as the material of DOE. The incident wavelength is 632.8 nm and the refractive index of the PMMA in the wavelength is 1.49. The thickness of the surface is 1.09 μm. We use nanolathe
to fabricate the surface, and add a 5-mm-thick PMMA as the substrate to clamp the element when fabricating
the surface. Fabricated DOE and its measurement results are shown in Fig. 4. The samples (diameter 7.1 mm)
were fabricated on a PMMA substrate (refractive index n = 1.49) at a max tuning depth 1.09 μm through nano
lathe. kinetic accuracy of the lathe rail is 10 nm. From Fig. 4(c,d), we can note that the size of the DOE is small
and the weight of it is 0.26 g. From the measurement result we can see that the sag of PMMA processed by nano-
lathe shows good agreement with the simulation. There is no notable step at different radius, so the diffraction
efficiency remains at a high level.

We use this PMMA element in the focal plane of the telescope and the results are shown in Fig. 4. In this
experiment, the calibration target used in this system is around 4 mm and the gap between the black stripes is
around 0.3 mm, which are shown in Fig. 5(a). From the image captured by CCD [Fig. 5(b)], we can see that the
image of the calibration target is not distinguishable after magnified by the telescope system. Moreover, the gaps
between the stripes are completely unresolved at the imaging plane of the system. However, after applying the
DOE in the focal plane [Fig. 5(c)], the horizontal stripes in the middle field are clear and the other stripes are
distinguishable as well. The gap between each stripe is resolvable, which means that the resolution of the system is
remarkably improved. However, distortion appeared as the image becomes distinct after insert the DOE.

Discussion
In summary, we simulate the performance of DOE as a field-flatting lens in the eyepieces of a well-designed
reflective telescope. The spot radius of the system at different FOVs is greatly shrined and the MTF of the sys-

Figure 5. The experimental result of the image of the telescope system, (a) is the calibration target and the
background circle is the location hole of the optical table, whose diameter is 8 mm, the blue square represents
the area of (b,c), the red square represents the area of (d,e). (b,d) are the images without the DOE and (c,e) are
the images after using the DOE.

Figure 5. The experimental result of the image of the telescope system, (a) is the calibration target and the
background circle is the location hole of the optical table, whose diameter is 8 mm, the blue square represents
the area of (b,c), the red square represents the area of (d,e). (b,d) are the images without the DOE and (c,e) are
the images after using the DOE.

Methods
DOE fabrication. The DOE (diameter 7.1 mm) were fabricated on a 4-mm-thick PMMA substrate (n = 1.49)
at a maximum tuning depth 1.09 μm through nanolathe (Nanotech 250 UPL). The kinetic accuracy of the lathe
rail is lower than 100 nm per 75 mm in diameter, and the surface altitude accuracy is lower than 2 nm.
Experimental setup. Fig. 2 shows the schematic of the optical experimental setup, including a laser (532 nm), a pin-hole (diameter 0.1 μm), an objective lens (magnification rate = 25, numerical aperture = 0.4, working distance = 0.17), a test target (THORLABS R3L351P), a collimator lens and an objective lens (L2, diameter = 76.2 mm, f = 300 mm) and an eyepiece (L3, diameter = 30 mm, f = 60 mm) and a CCD camera (Micron MTP9P31, 2592*1944, pixel size 2.22 μm). The incident light passes through the pin-hole, an objective lens and then collimated as an parallel ray. The collimated light incidents into the objective lens L2. L3 is settled 360 mm away from L2 and the DOE we fabricated is settled 330 mm away from L2.

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Author Contributions
D.K. and K.W. initiated the idea. Y.W. performed the simulations, conducted the experiment, prepared the figures, D.K. and Y.W. drafted the manuscript. All authors contributed to the scientific discussion and revision of the article.

Additional Information
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