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博士論文の要旨

In addition to the 10 m Keck I telescope, which has been already in operation since 1994, there are several 8~10 m class telescopes under construction toward the end of the century. Near infrared observations on these telescopes with an adaptive optics system will enable imaging with diffraction limited spatial resolution better than 0.1 arcsec, about 5 times higher than that achieved without the adaptive optics system.

National Astronomical Observatory has been developing an adaptive optics system for the 8.2 m Subaru telescope Cassegrain focus scheduled to be in operation from 1998. Two near infrared instruments for imaging and spectroscopy will use this adaptive optics system.

The adaptive optics system consists of a correcting optics module and a wavefront sensor module. Since adaptive optics needs a reference star for the wavefront measurement, there must be a nearby star to the astronomical object that shares a common optical path through the turbulent atmosphere. Maximizing the sensitivity of the wavefront sensor is especially important because the most cases only faint reference stars are available. The sensitivity, i.e. wavefront measurement accuracy for a faint star, depends on the wavefront sensor design.

Due to its sophisticated nature, many alternative methods and design choices are possible in constructing an adaptive optics system are exist. However, no comprehensive study for optimizing the system design is yet available.

The present paper describes the following three critical issues regarding the designing and development of an adaptive optics system for practical common use operation;

1. Design optimizations of 1) the optical elements of a wavefront curvature sensor and 2) the geometrical pattern of the driving electrodes of the bimorph deformable mirror taking into account practical aspects of operation.

2. Evaluation of the wavefront sensing error for faint reference stars, taking

into account the atmospheric turbulence statistics and the actual control system.

3. Evaluation of expected performance of the adaptive optics system for near infrared astronomical observations with the 8.2 m Subaru telescope.

The present thesis discusses the above issues in the following sequence.

In Chapter 1, after an introduction which explains the history and the basic theory of an adaptive optics system, the functions of the important optical components for the adaptive optics system, i.e. wavefront sensors and deformable mirrors are discussed. Propagation of wavefront through a turbulent atmosphere and a few key concepts which define the performance of the AO system are described.

Chapter 2 describes the 8.2 m Subaru telescope project and the performance requirements and basic design of the Subaru Cassegrain adaptive optics system. It is shown that a 36 element wavefront curvature sensor and a bimorph deformable mirror were chosen for the Cassegrain adaptive optics system to achieve full correction at the infrared K-band and obtain a diffraction limited image.

In Chapter 3, the new methods and the results of three sets of simulations to derive the most optimized design parameters for the wavefront sensor, the deformable mirror, and the control algorithm of the Cassegrain AO system are described. Firstly, the results of a series of intensive and simulations to compare the performance of various wavefront sensors taking the photon noise and the read out noise into account are described in detail. The analysis led to the choice of a 36 element wavefront curvature sensor. Secondly, another set of simulations to derive the best performance of a 36 element bimorph mirror under the presence of atmospheric turbulence and telescope tracking error, are described. In this second set of simulations, it was shown that one can derive the highest performance by optimizing the geometry of piezo electrodes to drive the bimorph mirror. Thirdly, the performance of the AO system using these different levels of control algorithms was simulated assuming a few independent frozen turbulent layers flowing in different directions at different wind speeds. It was shown that a newly developed control algorithm using a linear time series model to optimize the control matrix based on the past wavefront measurement data gives a considerably better performance as compared with those given by simple classical gain optimization algorithms.

Chapter 4 describes the expected performance of the AO system for Subaru telescope based on simulations with the realistic parameters. The optical wavefront propagating on the deformable mirror and the curvature wavefront sensor were calculated considering the diffraction effect. From the wavefront sensor signals, and the deformable mirror deformations for compensation, the instantaneous PSFs were calculated time after time. The expected performances for observational instruments which will use the adaptive optics system are calculated. The isoplanatic angle, the sky coverage for guide star, the dynamic range and expected improvement in spectroscopic performance are also estimated from the PSFs predicted by these simulations.

Finally, in Chapter 5, the actual performances of the proto-type adaptive optics system, which was constructed by the AO group of National Astronomical Observatory of Japan based on the above-mentioned design considerations and verified in laboratory and on a 1.6 m telescope, are summarized. We succeeded in demonstrating to improve the spatial resolution of the stellar images by this AO system using a natural star from 1.1 arcsec (uncorrected) to 0.36 arcsec (corrected) at 2.5 μm. Additionally, an experiment using a holographic atmospheric turbulence simulator clarified that the improvement of a corrected image is in accordance with the theoretical prediction given by simulation described in Chapter 4.

In conclusion, the following achievements regarding the development of an adaptive optics system were made and described in the present thesis.

1. Performance comparison of a Shack-Hartmann wavefront sensor and a curvature wavefront sensor was made taking various noises involved into account. This consideration led to our choice of a 36 element wavefront curvature sensor for the Subaru Cassegrain AO system.

2. An optimization method for designing the geometrical configuration of the driving electrodes pattern of the bimorph deformable mirror for practical use was established and the actual optimized deformable mirror for the prototype AO system was constructed using this method.

3. New control algorithm taking into account spatio and temporal correlation of atmospheric turbulence, was established. This method was used to show that

the performance of the AO system can be considerably improved by taking the wind directions into account in defining the AO control matrix, especially when the turbulent atmosphere is represented by a few independent frozen turbulent layers.

4. Performance estimation method considering the realistic atmospheric turbulence and wavefront measurement error was established. The expected performances of the adaptive optics system for infrared observations, on a 8.2 m telescope, were evaluated base on these simulations.

5. The preliminary observational results of the actual performances of the proto-type adaptive optics system on a 1.6 m telescope, and laboratory test with artificial light source and a holographic turbulence generator, were described.

As an appendix, an original Atmospheric Turbulence Generator produced by using the Computer Generated Holograms (CGHs) is introduced. This was made for testing the adaptive optics system in laboratory. The hologram was made to regenerate the wavefront in the beam which caused the characteristics of the atmospheric turbulence. By moving the hologram in a plane perpendicular to the beam, one can generate the time variation of turbulence which corresponds to the frozen flow model of the atmospheric turbulence.

論文の審査結果の要旨

本論文は、国立天文台がハワイに建設を進めている口径８ｍの大型光学赤外線望遠鏡用の補償光学装置の開発・製作に関する研究成果をまとめたものである。その内容は、研究の背景を述べたイントロダクション、８ｍ望遠鏡のカセグレン焦点補償光学系の概要、光波面測定装置、可変形鏡、制御系の検討、大型光学赤外線望遠鏡補償光学系の予測性能、プロトタイプ補償光学系の性能実証実験、結論および付録としてホログラフィー法による波面乱れ発生装置の全７章からなる。

申請者はまず、大型望遠鏡を用いた可視光・赤外線での天体観測において、空間分解能を実質的に制限している地球大気による光波面擾乱について概説し、補償光学系の基本原理と、これまでの世界における技術開発の状況を第１章で解説している。第２章は国立天文台がハワイ島で建設を進めている口径８ｍの大型光学赤外線望遠鏡計画、そのカセグレン焦点で赤外線での解像度の向上を目標に設計製作が進められている補償光学系について紹介し、本論文がこの補償光学装置の実際の製作に関連して行った研究成果をまとめたものであることを説明している。第３章から第５章までが、本論文の主要部分である。

第３章では、補償光学装置を設計製作する上で、不可欠な３つの主要構成要素である、波面測定装置、可変形鏡、制御系のそれぞれについて、可能な方式の性能を具体的に比較検討し、最適な方式を決める方法について論じている。ハルトマン方式とアバランシュ光ダイオード単一光子検出器を用いて波面の二次微分（曲率）分布を測定する曲率センサー方式を比較して、近赤外線用の低次波面誤差の補償システムとしては、より暗い天体に対しても使用できる曲率センサー方式のほうが優れていることを定量的に示した。続いて、低次波面補正用の可変形鏡として最適なバイモルフピエゾ素子駆動型可変形鏡の具体設計に関して、バイモルフピエゾ素子の電極配列を計算機シミュレーションで最適化する方法を新しく開発し、実際に最適配置解を求め、この設計を基に可変形鏡を製作した。補償光学装置の制御についても、従来型の制御ゲインの最適化法に比べて格段の性能向上が実現できる、新しい線形結合行列による制御法を開発した。この制御法は実際の大気のゆらぎが、補償光学の時間尺度では擾乱がほぼ凍結されたまま風に流されていると考えて良いことを利用したものであり、実際に大気の乱れが風向風速の異なる複数の擾乱層により引き起こされている場合について、シミュレーションすることにより、従来のゲイン調整法に比べて格段の改善となる可能性が高いことを実証した。

第４章では、申請者が研究開発したこれらの主要構成要素を実際の補償光学系として組み上げ、口径８ｍの大型光学赤外線望遠鏡に装着した場合の期待される性能を、大気のゆらぎ、補償光学系に内在するさまざまな誤差要因、波面誤差測定用に利用できるガイド星の明るさなどをとりいれた、現実的なシミュレーションの方法を開発し結果を求めた。

第５章では申請者のグループで自作したプロトタイプ補償光学装置を実際に望遠鏡に装着した時の性能測定結果を、第４章で開発した性能予測シミュレーションの結果との比較を行い、両者が一致することを確認した。この性能評価実験を室内で行うときには大気のゆらぎとよく似た空間スペクトルと時間変動を持つゆらぎを発生させることが課題となるが、申請者が開発した計算機によるホログラムを用いた独創的なゆらぎ発生装置について、付録として第７章でその原理などを説明している。

これらの研究成果は第6章に結論としてまとめられている。

補償光学装置の開発研究については、国際的にも先陣を争う研究分野である。また大型装置であることから共同研究の部分もあるが、本論文で述べられている第3章から第5章、および第7章の研究は申請者が独自に行った独創的なものであり、国際的にも高いレベルにあり、審査委員全員は本論文が大型望遠鏡の補償光学装置の開発に新しい知見をもたらしたものであると評価し、博士論文として十分な内容のものであると判断した。