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(別紙様式 2)
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# 論文の要旨
## Summary (Abstract) of doctoral thesis contents


Several thousand exoplanets have thus far been discovered using indirect methods, such as transit and radial velocity, but very few using direct imaging. To answer questions about the habitability of exoplanets, it is essential to utilize direct detection methods in order to be able to conduct spectroscopic studies. Direct imaging of habitable exoplanets is challenging, as the planet is orders of magnitude fainter than the host star (reflected light from an Earth-like planet is a billion times fainter than its Sun). Upcoming extremely large telescopes (ELTs) will be able to image habitable exoplanets in reflected light around M-type stars, thanks to more moderate planet/star contrast. At present, the field of high-contrast imaging is able to image young Jupiter-size exoplanets with current 8-10 m class telescopes. There will be new limitations and error terms faced by ELTs to achieve such large contrasts such as those required for terrestrial planets, which are not dominant at current telescopes. Chromatic errors will have a significant effect on the performance of adaptive optics (AO) and for high-Strehl ratio performance, closed-loop correction of atmospheric dispersion will be required.

The basic architecture of a high-contrast instrument consists of an extreme adaptive optics (ExAO) systems to compensate for atmospheric turbulence and coronagraphs to suppress the light coming from the host star to enable imaging of exoplanets. For ground-based high-contrast instruments, a potentially significant source of coronagraphic leakage comes from low-order aberrations such as tip/tilt and residual atmospheric dispersion. Traditionally, the atmospheric dispersion is compensated for by an atmospheric dispersion compensator (ADC). The ADC control relies on an a priori model of the atmosphere whose parameters are solely based on the pointing of the telescope (the model often also includes temperature and pressure as an input), which is too simplistic and can result in an imperfect compensation, leading to some residuals. For a high-contrast instrument like the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system, which employs very small inner working angle coronagraphs, refraction-induced smearing of the PSF (atmospheric dispersion) must be kept to <1 mas across H-band for optimum performance. Theoretical models currently used for atmospheric dispersion correction are indeed precise enough for the requirements stipulated above, however, these models are limited by the precision of the environmental parameters that are input into them.

The SCExAO instrument is a multipurpose high-contrast imaging platform designed for the discovery and detailed characterization of exoplanetary systems and serves as a testbed for high-contrast imaging techniques and technologies for ELTs. Currently, SCExAO is undergoing commissioning and it has started to image exoplanets.

In this thesis, I present a new approach for the closed-loop measurement and subsequent correction of atmospheric refraction in the science image itself. The work presented in the thesis shows that, for a very precise correction of dispersion, it is important to measure and correct it in the final science image rather than rely on the theoretical calculation alone.

The measurement of residual dispersion in the final science image uses the chromatic scaling of the focal plane

calibration speckles. The focal plane speckle can be generated by diffracting the PSF by a deformable mirror or a transparent grating. Due to the wavelength dependence of speckles, in the presence of no dispersion (in the PSF) speckles radiate (point towards) from the PSF core and we call this point the radiation center. In the presence of dispersion, speckles no longer point towards the PSF core and the radiation center moves away from the PSF core. Simulations were carried out to test the concept. Subaru Telescope pupil was used to simulate the PSF with atmospheric dispersion and speckles were generated by diffracting light in the pupil. The presence of dispersion in the PSF was measured by establishing an empirical relationship between the deviation of the radiation center from the PSF core. There is a direct relationship between the amount of dispersion to the deviation of radiation center from the PSF core, which was established by simulation. So by measuring the distance between the radiation center and the PSF core, one can directly estimate the amount of residual dispersion on-sky. The location of the radiation center was measured by a raster scan around the PSF core to minimize the norm of the difference between original and stretched speckles, the minimum provides a high-precision measurement of the radiation center. This concept and method of quantifying the amount of atmospheric dispersion were developed for the first time throughout the course of this thesis.

After verifying the concept and measurement technique via simulation on-sky testing was conducted. The on-sky measurement of the dispersion was done by using an adaptive speckle grid generated using the DM of SCExAO. The on-sky speckles were placed at 22.5 λ/D, with a 100 nm RMS amplitude. The data was collected using Subaru Telescope facility instrument AO188 and AO correction from SCExAO was not utilized. The images were taken using an internal near-infrared (NIR) camera inside SCExAO. The successful on-sky measurement of residual dispersion was achieved on the target Alpha Ari, on SCExAO's engineering night of October 30th, 2015. The measured value of the residual dispersion was 7 mas in H-band, which was corrected to 1.4 mas by driving the science path ADC inside AO188.

On-sky closed-loop correction of residual atmospheric dispersion was achieved on the target Beta Andromedae on one of SCExAO's engineering nights, namely September 19th, 2016. The closed-loop measurement and correction were performed for two loop gains of 20% and 50% and the loop converged faster for a loop gain of 50%. However, both the loops converge approximately to the same level of correction. The value of residual dispersion in y-H band went from 20.73 mas to 2.8 mas, which corresponds to a reduction in the PSF elongation from 11.04 mas to 0.49 mas in H-band after closing the loop. Here a successful demonstration of a closed-loop correction of atmospheric dispersion was achieved, which provides a better compensation compared to a single step correction.

For the next steps in on-sky testing, an open loop measurement of dispersion was carried out for various telescope elevations to answer the following question:

- Test the performance of look-up table based ADC correction as a function of telescope elevation and varying atmospheric conditions.
- Estimate the presence of dispersion due to internal optics.
- Understand sources contributing to the presence of residual dispersion in the final science image and how frequently it needs to be corrected.

The on-sky measurement of residual atmospheric dispersion was performed on the target beta Andromedae on the

SCExAO engineering night of September 19th, 2016. During the 30 min window of data collection, a relatively small increase in the residual dispersion was observed as a function of decreasing elevation angle, which was consistent with theory.

To determine the effect of large elevation angle changes on residual dispersion, the experiment was repeated on December 13th, 2016 on the targets alpha Ari and 51 Eri with significant changes in the telescope elevation. The conclusion of the measurement was that compensation of atmospheric dispersion by the ADC was not optimum and on-sky dispersion values have a constant offset, which was due to the presence of dispersion from the internal optics. The presence of dispersion due to internal optics was estimated, which was found to be 18.9 mas in the y-H band (elongation in the PSF). As a conclusion, the presence of dispersion due to internal optics can lead to imperfect compensation, even when the theoretical look-up table utilized for compensation is accurate. Which is expected as the model is not aware of any instrumental biases. It was observed that even after accounting for the instrumental dispersion, the compensation by the ADC was not optimal. Which was due to the varying condition of the atmospheric parameters. On the night of the observation, it was determined that the low values of temperature and relative humidity led to the overestimation of dispersion by the ADC.

In this thesis, I present a new focal plane based technique to measure residual atmospheric dispersion directly in the science image. The work presented here offers a way to measure residual dispersion to a high-precision and apply a correction by a fine control of the ADC, as an offset to the model-based correction presently used. On-sky closed-loop correction of dispersion by driving the ADC was also validated. In closed-loop a correction precision of <1 mas of elongation in the PSF across H-band was achieved.

Finally to test the performance of closed-loop correction of atmospheric dispersion on coronagraphy. On-sky testing of light leakage through a high-performance coronagraph such as vortex was carried out. In a closed-loop correction of dispersion, the vortex coronagraph performed better in flux suppression compared to the look-up table based correction of dispersion.

We observed that the residual dispersion does not change significantly as a function of time or elevation, therefore very small corrections at low cadence are needed to implement a high level of correction as long as atmospheric conditions do not vary drastically during the observation. Finally, by using a method which uses the science image to correct for residual atmospheric dispersion, it is possible to correct for dispersion resulting from optics internal to the instrument as well. The effect of optics is not taken into account in ADC models, so direct measurement of this effect in the focal plane is the only solution. This work can also be used as a diagnostic tool to measure the dispersion due to internal optics in the science image.

In the era of ELTs, This work will be valuable in the field of ground-based high contrast imaging to directly image and perform high-precision astrometric measurements of terrestrial exoplanets.

(別紙様式 3)
(Separate Form 3)

# 博士論文審査結果の要旨

Summary of the results of the doctoral thesis screening

太陽系外の惑星(系外惑星)は、1995年に精密視線速度法により初めて発見されて以来、精密視線速度法とトランジット観測の発展により、これまでに3000個を超える数が発見されている。しかしながら、惑星の性質を明らかにする上で最も有効な方法である直接撮像が成功した例は、未だ40個余りに留まっている。この主な理由は、主星と惑星の明るさに何桁にも及ぶ大きな差が存在し、かつ、主星と惑星の間の見かけの距離が近いために、惑星からの放射が主星の光に隠されてしまうからである。近年、大型望遠鏡における補償光学装置およびコロナグラフ装置が大きな進展を見せており、主星に近接した惑星の直接撮像を行う努力が続いている。特に、生命居住可能な領域、いわゆるハビタブルゾーンに存在する惑星の直接検出は、宇宙における生命探査につながる重要なステップと考えられており、世界中で活発な研究が行われている。

出願者は、すばる望遠鏡に搭載されている極限補償光学装置SCExAOの開発チームに属し、極限補償光学およびコロナグラフ装置の性能を向上させるための取り組みを行ってきた。極限補償光学により星像を回折限界に近づけ、より高いコントラストを狙ったコロナグラフ装置では、今までは問題にならなかった色分散補正の誤差がコントラスト低下の主要な原因の一つとなる。大気による色分散は、通常、三角プリズムを二枚組み合わせたADC（Atmospheric Dispersion Corrector）によって補正する。SCExAOの前段となる補償光学装置であるAO188にはADCが内蔵されており、SCExAOの観測波長域である近赤外線において、色分散は要求仕様の10ミリ秒角以下に抑えられている。しかし、極限補償光学において主星のごく近傍で超コントラストを目指す場合、Hバンドにおいて1ミリ秒角以下に色分散を抑える必要があり、現在のADCをそのまま運用しても必要な要求精度を達成できない。

そこで出願者は、高精度に色分散を計測・補正するための方法として、波面補償のための可変形鏡を用いて検出器上に星像の干渉パターン（スペックル）を形成し、そのパターン解析から現行ADCで補正しきれていない残存色分散を求める方法を開発した。色分散が存在すると、スペックルの放射中心と星像中心との間にズレが生じる。このズレ量をゼロにするようにADCにフィードバック制御をかければ、地球大気から検出器までで発生する色分散をほぼ完全に補正できる。このような手法によって色分散を補正する試みはこれまでにされたことはなく、出願者のアイデアは極めてユニークである。出願者は数値シミュレーションによってアイデアを検証し、データ解析およびフィードバック制御ソフトウェアを開発、実験室での実験を経て、最後にすばる望遠鏡を用いた観測によってオン・スカイ（実地）での性能確認を行った。その結果、Hバンドにおいて約8ミリ秒角あった残存色分散を0.28ミリ秒角まで抑えることに成功し、極限補償光学に求められる性能が達成可能であることを示した。また、AO188＋SCExAOシステム内部の光学系に起因する色分散を残存大気色分散から分離することに成功し、システムの性能向上のための基礎データを得た。

さらに出願者は、今回開発した手法をSCExAOを用いた高コントラストコロナグラフ観測に応用し、残存色分散の補正がコロナグラフ性能にどのように影響するかを調べた。その結果、星像中心から100ミリ秒角以内への光の漏れ量が約40％低減することを確認した。本研究で用いられた極限補償光学における色分散測定・フィードバックシステムは出願者

が中心になって開発したものであり、数値シミュレーションの遂行から、初期実験、オン・スカイ実証、結果のとりまとめ、議論など、論文作成の一連の過程において、出願者が主体的に行っていることが認められ、その内容は将来の極限補償光学の性能向上に大きく貢献するものである。したがって、審査委員全員が博士論文として合格であると判断した。