The Overview and Trial Observations of AIMS Postprint

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Abstract

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Full Text

Preamble

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The Overview and Trial Observations of AIMS

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Abstract

The infrared band offers rich opportunities for astronomical research, but due to limitations in infrared technology, the development of infrared astronomy in China has long been unsatisfactory, particularly for solar observations. The "Accurate Infrared Magnetic field Measurements of the Sun" project (AIMS) is a National Major Scientific Research Instrument Development Project (recommended by the Ministries) supported by the National Natural Science Foundation of China. It aims to improve magnetic field measurement accuracy by an order of magnitude through direct measurement of Zeeman splitting. Additionally, as AIMS represents the world' s first equipment specifically designed for mid- to far-infrared solar observation, we hope to utilize it to explore potential new scientific research opportunities in this vast infrared region. This article briefly introduces the scientific objectives, telescope design, scientific post-focus instruments, and summarizes the commissioning observations of AIMS.

Key words: Sun: infrared –methods: observational –instrumentation: spectrographs

1. Introduction

Magnetic fields play a crucial role in understanding the mechanisms of solar and stellar activities. Since Hale (1908) first measured the solar magnetic field, solar and space physics has made great progress across broad aspects related to solar magnetism. To date, several methods exist for measuring solar magnetic fields, but the approach pioneered by Hale based on the Zeeman effect remains the most effective and widely used.

The fundamental principle of magnetic field measurement using the Zeeman effect is that spectral lines undergo splitting in magnetized solar atmospheres. The separation between these split spectral sub-lines is proportional to the magnetic field strength, with the specific functional relationship given by:

Here, g is the effective magnetic sensitivity factor (e.g., Landé factor), λ is the central wavelength in Angstroms, $\Delta\lambda$_B is the separation from the line center, and B is the magnetic field strength in Gauss. Moreover, these split spectral lines exhibit different polarization states.

For specific spectral lines, the Landé factor and wavelength are fixed. Therefore, theoretically, once the Zeeman splitting distance is measured, the magnetic field strength can be determined. However, in current routine magnetic field observations in the visible and near-infrared bands, the Zeeman splitting is extremely small compared to the width of solar spectral lines, making direct measurement difficult in most cases. An effective alternative is to exploit the different polarization states between Zeeman sub-lines by conducting polarization measurements and inverting these polarization profiles using the theory of polarized radiative transfer in the solar atmosphere to obtain magnetic field information (Unno 1956).

Consequently, current mature methods for measuring solar magnetic fields essentially convert the problem into measuring polarization parameters of solar spectral lines. This "indirect measurement" approach means that results strongly depend on the radiative transfer model of the solar atmosphere. Unfortunately, determining the solar atmospheric model requires many physical parameters that are often not directly accessible and can only be inferred from the local solar atmospheric environment without guaranteed accuracy. This leads to issues such as non-uniqueness and limited precision in inversion results (del Toro Iniesta & Cobo 2016). Furthermore, since the magnetic field itself is an important parameter in the model, the inversion process becomes somewhat circular. This dependence on solar atmospheric models represents a significant drawback of existing magnetic field measurement methods.

Additionally, these methods suffer from another limitation: sensitivity to transverse magnetic field components is much poorer than to longitudinal components. Through simple assumptions, J. Evans (1966) provided an estimate of the relationship between sensitivities to longitudinal and transverse components, where B_T represents sensitivity to transverse components (perpendicular to the line of sight) and B_L represents sensitivity to longitudinal components (along the line of sight). Consequently, even though current solar magnetic field telescopes can achieve longitudinal magnetic field measurement sensitivities of several Gauss, transverse field measurement sensitivity remains only on the order of tens to hundreds of Gauss (Deng et al. 1999; Jin et al. 2009), significantly limiting accurate magnetic field strength measurement.

Because Zeeman splitting is proportional to the square of the wavelength while solar spectral line width is generally proportional to the first power of wavelength, the splitting induced by the Zeeman effect becomes much more pronounced relative to line width in the mid- and far-infrared bands due to the large wavelengths in these regions. Brault & Noyes (1983) pointed out that under the same Landé factor, Zeeman splitting in mid-infrared spectral lines is more than two orders of magnitude greater than in the visible region, with the relative width of Zeeman splitting to spectral line being more than 25 times higher than in visible light under equivalent conditions. Therefore, the mid-infrared band offers potential for directly measuring Zeeman splitting, which could transform traditional "indirect measurement" back into "direct measurement," thereby improving magnetic field measurement accuracy and reducing dependence on solar atmospheric models. This approach would eliminate reliance on radiative transfer models. Moreover, by converting traditional polarization intensity measurements into polarization profile position measurements, the impact of instrumental polarization and crosstalk would be significantly reduced, greatly improving magnetic field measurement accuracy.

Given these potential advantages of mid- and far-infrared observations, scientists began exploring the scientific value and technical feasibility of infrared solar observations in the 1970s. Representative achievements included experimental observations at the Mg I 12.32 m line using the McMath-Pierce Solar Telescope, the largest solar optical telescope at that time. These studies included work by Hewagama et al. (1993) and Moran et al. (2000), who used a BIB (Blocked Impurity-Band) detector combined with an FTIR (Fourier Transform Infrared Spectrometer) to obtain complete Stokes parameters for a point source in 7 minutes. Additionally, Jennings et al. (2002) and Moran et al. (2007) used a BIB 128 × 128 array detector with a grating spectrometer, achieving a spectral resolution of approximately 0.6 nm and completing Stokes spectroscopic measurements of line sources within 5 minutes. These pioneering works demonstrated the feasibility and advantages of magnetic field measurements in the mid- and far-infrared. However, since these efforts used experimental equipment, they did not establish a systematic scientific observation and research framework.

In recent years, infrared observations have advanced significantly with the implementation of infrared scientific terminals on the Goode Solar Telescope (GST), the GREGOR telescope, and the Daniel K. Inouye Solar Telescope (DKIST) (Schmidt et al. 2012; Rimmele et al. 2020; Yang et al. 2020). DKIST currently operates two infrared terminals: the Diffraction-Limited Near-Infrared Spectro-Polarimeter (NIRSP) and the Cryogenic Near-Infrared Spectro-Polarimeter (CRYO-NIRSP). Schad et al. (2024) reported coronal magnetic field observations using CRYO-NIRSP. The Cryogenic Infrared Spectrograph (CYRA) on GST focuses on solar spectral observations between 1 and 5 m and has been conducting observations for several years (Yang et al. 2020). Judge et al. (2024) used the GREGOR Infrared Spectrometer (GRIS) to analyze magnetic field changes from the photosphere to the upper chromosphere. Although infrared solar observations have made substantial progress, magnetic field measurements have primarily been conducted in the near- and mid-infrared below 5 μm, failing to fully leverage the advantage of “direct measurement” of solar magnetic fields in the mid- and far-infrared.

The “Accurate Infrared Magnetic field Measurements of the Sun”project (AIMS) was proposed based on these scientific considerations. Supported by the National Natural Science Foundation of China in December 2014 through the National Major Scientific Research Instrument Development Project (recommended by the Ministries), AIMS officially launched in May 2016. It has now completed all development work and been installed at Saishiteng Mountain in Lenghu, Qinghai Province, where scientific trial observations began in September 2023.

This paper briefly introduces the scientific objectives, telescope design, and scientific post-focus instruments of AIMS in Section 2, demonstrates its scientific observation capabilities through commissioning data in Section 3, and provides a summary and discussion in Section 4.

2.1. Scientific Objectives and Top-level Design Requirements

2.1.1. Scientific Objectives

The core scientific objective of AIMS is to establish a mid-infrared measurement system for solar observations, thereby breaking through persistent bottlenecks in solar magnetic field measurements: the reliance on solar atmospheric models when inverting polarization measurements to magnetic fields, and the significantly lower measurement accuracy of transverse components compared to longitudinal components. AIMS aims to improve current measurement accuracy of solar magnetic field strength by approximately an order of magnitude, achieving a precision of 10 Gauss. Through more precise and quantitative observational data on solar magnetic fields, AIMS expects to achieve groundbreaking results in solar physics research.

2.1.2. Top-level Design Requirements around Scientific Objectives

To achieve direct measurement of Zeeman splitting, appropriate mid-infrared solar spectral lines must be selected, and the split spectral profiles obtained using a spectrograph. By determining the line center positions of the split spectral sub-lines, the Zeeman splitting can be obtained, allowing direct derivation of solar magnetic field strength information using the Zeeman splitting formula. There are significantly fewer magnetically sensitive spectral lines available for magnetic field measurements in the mid-to-far-infrared compared to the visible region. The Mg I 12.3 μm line, which forms in the solar “temperature minimum zone," has a Landé factor of 1. Hewagama et al. (1993) successfully observed its triplet spectral lines using this line at the McMath-Pierce Solar Telescope at Kitt Peak. Therefore, AIMS has also selected it as its operating wavelength.

Obtaining magnetic field strength directly through Zeeman splitting measurement requires high spectral resolution, posing a significant technical challenge for an infrared spectrograph. Therefore, appropriate specifications must be determined to achieve an optimal balance between scientific objectives and engineering feasibility. Based on simulation analysis of the Mg I 12.32 m spectral line characteristics, the spectral resolution specification for AIMS was determined to be 0.004 cm^{-1}, enabling a measurement accuracy of 10 Gauss.

In the mid-infrared band, Fourier Transform Infrared Spectrograph (FTIR) is almost the only option to achieve such high spectral resolution, with a spectral resolving power of approximately 0.004 cm^{-1} (corresponding to 0.06 nm @ 12.32 m). Therefore, the core scientific instrument of AIMS is the FTIR and its matching high-performance infrared detector. Simultaneously, considering the needs of imaging observations for solar physics research, we require the FTIR to have large field-of-view imaging capability—a user requirement that no international FTIR supplier had previously encountered, thus becoming a major technical challenge and innovation point in this project' s development.

Currently, achieving a large array of high-performance infrared detectors matching the FTIR is challenging, so the project proposes a 64 × 2 line array detector. Under this constraint, to guide the FTIR in selecting and positioning observation targets and to facilitate joint analysis with data from other instruments, AIMS has also designed an 8-10 m mid-infrared imaging system to complement FTIR observations. The main performance and design parameters of AIMS are shown in Table 1.

2.2. Telescope

2.2.1. Optical Design of the Telescope

AIMS adopts a classic off-axis Gregorian system featuring a primary mirror (M1) with a clear aperture of 1 m and an off-axis distance of 1 m. The optical design is shown in Figure 1 [Figure 1: see original paper]. A field stop with a diameter of Φ 6.4 is placed at the focus of the primary mirror. Mirrors M3-M6 constitute a Coudé system. M4 serves as an ellipsoidal relay mirror, extending the Gregorian focus to the desired position (intermediate focus). Mirror M6 reflects the chief ray and directs it vertically toward the Coudé room, aligning with the horizontal mechanical rotation axis. A derotator system is positioned in front of the intermediate focus. M7 is an off-axis parabolic mirror that converts light from the intermediate focus into collimated light for subsequent focal plane instruments and detection optics. Mirror M8 folds the optical path, while the 45° mirror M9 at the pupil position is replaced by a tip-tilt mirror, also serving as a folding mirror. M10 reflects light in the 12.32 m and 8-10 m wavebands while transmitting light in other wavebands.

A polarization analyzer is placed in the collimated beam of the 12.32 m optical path, after which the beam is converged by a lens to serve as the interface for the FTIR. Cold optics are positioned between the FTIR and detector, where the cold stop of the telescope system is formed, thereby eliminating stray light outside the field of view. The M11 beamsplitter reflects the 8–10 m beam for wide-band imaging while transmitting light of other wavelengths. The visible light, after being reflected by M11 and split by M12, is divided into two channels: 550 ± 5 nm wavelength light is used for image tracking and pupil tracking, while 630 ± 5 nm wavelength light is utilized for tip-tilt mirror monitoring and wavefront detection.

The key specifications for the AIMS optical system are as follows (Table 2):

Figure 2 [Figure 2: see original paper] presents the imaging quality test results for the center field of each AIMS focus at -10°C, all of which meet system design requirements.

2.2.2. Mechanical Design of the Telescope

The AIMS telescope structure primarily consists of the primary and secondary mirror mount assembly, a two-dimensional tracking turntable assembly, the support structure for the intermediate folded optical system, and the post-optical system structure within the Coudé room. The main structure of the AIMS telescope (located in the Dome section, shown in Figure 3 [Figure 3: see original paper]) primarily adopts a truss or steel plate welding design, with a total weight of approximately 15T (including counterweights). The outer envelope dimensions are 4268 mm × 2960 mm × 5788 mm, and the rotational contour diameter is Φ 5557 mm. The surface accuracy of the primary mirror (shown in Figure 4 [Figure 4: see original paper]), as measured on-site at 20°C, is better than 1/40 λ @ 632.8 nm.

A fully absorbing thermal aperture is installed at the focus of the primary mirror with an aperture of Φ 4.25 mm. The hot stop design is shown in Figure 5 [Figure 5: see original paper]. The thermal aperture is cooled and temperature-controlled using a coolant, with temperature maintained within less than 5°C of the ambient environment to minimize seeing impact caused by local temperature differences at the primary mirror focus.

The secondary mirror is precisely adjusted using a PI 6-axis hexapod (Shen et al. 2022), with adjustment accuracies of 2 m for translation and 5 rad for tilt. The six-rod mechanism facilitates real-time correction of positional errors caused by temperature and attitude changes in the primary and secondary mirror mounts. To obtain the Look-up Table (LUT) for the 6-axis hexapod at different pitch angles, we developed a point source Shack-Hartmann wavefront sensor. Based on nighttime measurement data, we found that relative positioning errors between M1 and M2 at different pitch angles are primarily tilts in the horizontal and azimuthal directions. Therefore, we constructed LUTs for tilt alignment amounts in the horizontal and azimuthal directions at different pitch angles (24°–71°), as shown in Table 3 . During daytime observations, M2 position is adjusted based on the LUT for different pitch angles to ensure AIMS imaging quality. The measured data indicates that the 6-axis hexapod LUT significantly improved image quality, proving the method effective and practical. The measured data will be presented in Section 3.3.

The telescope achieves precise tracking through a two-dimensional tracking turntable. The AIMS pointing and tracking control system (shown in Figure 7 [Figure 7: see original paper]) is designed as a distributed, modular control system, with each module functioning relatively independently and integrated using Ethernet and fieldbus configuration. Based on functional structure, the system is divided into eight functional sub-blocks, with core modules comprising the azimuth axis servo control system, elevation axis servo drive system, derotation servo control system, and full-disk opto-electronic guiding system. To ensure system safety, openness, controllability, and ease of expansion and maintenance, a safety and logic interlock system, remote control interface and operation and maintenance database system, operating environment and telescope status monitoring system, and strong/weak electricity distribution system have been designed. The servo systems for the azimuth, elevation, and derotation axes have high real-time requirements, so separate controllers are used. Meanwhile, the full-disk opto-electronic guiding system, entrance pupil image monitoring system, and PLC status monitoring and logic control system, due to their lower real-time requirements and for operational convenience, are integrated into the central control computer platform. The closed-loop tracking test error of AIMS is shown in Figure 8 [Figure 8: see original paper], achieving pointing and tracking accuracies of 5.91 (rms) and 0.76 (rms@30 minutes), respectively. Additionally, the AIMS telescope adopts a five-mirror derotation structure (shown in Figure 6 [Figure 6: see original paper]) to greatly reduce polarization impact (Hou et al. 2018). However, this complex structure presents new challenges for assembly and adjustment. We achieved a co-axiality error of $±$10.53 between the incident optical axis and the mechanical rotation axis of the derotation mechanism using two laser theodolites, a pentaprism, and other tools. The specific assembly method can be found in Lei et al. (2023).

2.3. Scientific Instruments

Currently, AIMS is primarily equipped with a 12.32 m FTIR system and an 8–10 m wide-band imaging system. In the future, the possibility of extending a visible light observation system in the imaging tracking optical path may be considered.

2.3.1. FTIR (Infrared Fourier Transform Spectrograph)

The working principle of AIMS/FTIR is shown in Figure 9 [Figure 9: see original paper]. Infrared radiation from the target enters the interferometer from the front, then passes through subsequent optics that map the detected infrared radiation onto the detector. The light signal received by the detector is the infrared radiation signal modulated by interference, referred to as the interference signal. The interference signal is processed through a Fourier transform to obtain the spectral signal of the radiation. The FTIR can be configured to observe with five different bandwidths: 12.32 ± 0.05 m, 12.32 ± 0.1 m, 12.32 ± 0.2 m, 10-11 m, and 10-13 m. The spectral resolution is better than 0.004 cm^{-1} (FWHM) @12.32 m, corresponding to a requirement for an optical path difference of at least 250 cm. The optical path difference is generated by movement of the interferometer' s moving mirror. The FTIR interferometer has a quadruple-pass structure, with a theoretical moving mirror travel distance of at least 62.5 cm.

In design, the FTIR employs a 128-element Mercury Cadmium Telluride (HgCdTe) detector. Because spectral detection in the central field of view is more effective than in the edge field, observation quality is better closer to the optical axis. Thus, the 128-element detector is arranged in a 64 × 2 format—2 columns with 64 elements each—as shown in Figure 10 [Figure 10: see original paper]. The measured detectivity of each detection unit is better than 4×10^{10}, as shown in the test results (Figure 11 [Figure 11: see original paper]). The spectral resolution of a typical unit is presented in Table 4 , with all indicators meeting or exceeding design values.

2.3.2. 8-10 m Wide-band Imaging System

The 8-10 m Wide-band Imaging System is primarily designed for solar imaging monitoring. Its main objective is to obtain evolutionary information about solar atmospheric activities in the mid-infrared band, which is of great significance for studying the evolution mechanisms of white-light flares and other phenomena in this spectral range. The system consists of three primary components: an optical system, a vacuum refrigeration system, and a data acquisition and control system for the detector (Wang et al. 2022; Feng et al. 2025). The overall sketch of the Mid-IR ITS is displayed in Figure 12 [Figure 12: see original paper]. A 256 × 256 Mercury Cadmium Telluride (HgCdTe) focal plane array detector is employed with a pixel size of 30 × 30 m. It is connected to the rear end of the AIMS telescope, offering a field of view of Φ 384 with a pixel resolution of 1.5 pixel^{-1}. The system is equipped with multiple narrowband filters that can be switched according to observational requirements to select different wavelength bands and bandwidths for imaging. Table 5 lists the main performance and key parameters.

2.4. The Site

AIMS is located at Saishiteng Mountain, Qinghai, China (as shown in Figure 13 [Figure 13: see original paper]). Since 2018, we have installed a weather station, a precipitable water vapor spectrometer, and a solar equivalent of a Differential Image Motion Monitor (S-DIM), conducting observations of meteorological elements, precipitable water vapor, and daytime seeing conditions for over one year at this site. The median daytime precipitable water vapor value is 5.25

mm for the entire year and 2.1 mm in winter. The median Fried parameter for daytime seeing is 3.42 cm. Solar direct radiation data shows that the average observable solar time is 446 minutes per day in August 2019. Details about the site survey can be found in Bao et al. (2023).

3. Commissioning Observations

AIMS began trial observations on August 31, 2023, and as of October 20, 2024, has observed for a total of 149 days, generating 24.7 TB of raw data. Among these, FTIR observations were conducted for 120 days, producing 23.1 TB of raw data, while the 8-10 m imager observed for 119 days, yielding 1.57 TB of raw data. Through more than a year of trial observations, observation modes and calibration methods for the two focal plane scientific terminals have been established and integrated into the AIMS observation control system, enabling automatic observations. Below are some trial observation results.

3.1. Accuracy of Magnetic Field Measurement

AIMS has achieved solar spectral observations using a line-source FTIR for the first time worldwide, significantly enhancing FTIR observational efficiency. Figure 14 [Figure 14: see original paper] presents the spectral image of Mg I 12.32 m taken by the 128-element detector of AIMS/FTIR. The observation and processing workflow for the spectral image primarily includes: The FTIR obtains a set of 128-element interferograms every 30 s, with 16 measurements conducted in total over 480 s. Spectral inversion for each of the 128 elements is performed using the method proposed by Bai et al. (2021) and Bai et al. (2023). There is inhomogeneity among inverted spectra of different pixels. By utilizing the quiet region at the center of the solar disk and employing a random jittering method of the telescope, different flat field calibration matrices are obtained and applied for flat field correction. After flat field correction, spectral drifts still exist among different pixels, which are corrected using atmospheric spectral lines near Mg I 12.32 m.

Figure 14 (upper) clearly shows the triple-split feature of the sunspot penumbra, demonstrating the advantage of the high magnetic field sensitivity of Mg I 12.32 m. The emission intensity of Mg I at 12.32 m is relatively weak in the umbra, consistent with observations made by Bruls et al. (1994) using a point source Fourier Transform Infrared spectrometer. Figure 14 (bottom) presents the inverted spectrum of the 40th element, with the Zeeman splitting distance of the Mg I 12.32 m line obtained using a triple-Gaussian fitting method. The magnetic field strength is calculated based on the Zeeman splitting formula, with the standard deviation (1σ) of the fitting serving as the measurement accuracy. The fitting result is shown as the solid black line, with a fitted magnetic field strength of 1346 G and a strength measurement error of 8.4 G.

In addition to measuring a 64 × 2-element spectrum in a single observation, AIMS can also cover a two-dimensional area of the solar surface through scanning observational mode. Figure 15 [Figure 15: see original paper] presents an intensity image of NOAA AR13796 obtained from a set of scans, with the umbra and penumbra distinctly identified.

3.2. Polarization Measurement

By measuring Zeeman splitting, only the total magnetic field strength can be determined; information on magnetic field inclination and azimuth cannot be obtained. Thus, polarized spectral observations are also necessary. Additionally, polarized observations can provide magnetic field information in regions without triple splitting. Figure 16 [Figure 16: see original paper] presents a set of 128-element Stokes I, Q, U, V polarized spectral images observed on April 22, 2023. For Stokes Q and U linear polarization, axisymmetric spectral profiles can be observed, while for Stokes V circular polarization, centrally symmetric spectral profiles are visible, consistent with spectral symmetry calculated by polarized radiative transfer theory.

The emission characteristics of the Mg I 12.32 m line are caused by non-local thermodynamic equilibrium (NLTE) processes, which must be considered in the inversion of polarized spectra. We used the STockholm Inversion Code STiC (de la Cruz Rodríguez et al. 2019) to perform NLTE inversion of the 108th element in Figure 16. The NLTE inversion can yield the temperature distribution as a function of height, as well as information on total magnetic field strength, inclination, and azimuth. The inversion result is shown in Figure 17 [Figure 17: see original paper].

3.3. Spatial Resolution in the Visible Wavelength

We also obtained high-quality visible light images during commissioning observations through the image tracking system. The quality of these visible light images is evaluated by Median Filter-Gradient Similarity (MFGS), which screens the best image within sequences of short-exposure tracking images. MFGS is a quality evaluation method for solar photosphere images that does not require a reference image, featuring monotonicity (MFGS value changes monotonically from 1 to 0 with image quality degradation), linear correlation, and universality (Deng et al. 2015).

From September 2023 to December 2024, the image tracking system accumulated observations over 146 days. The MFGS value of the best single-frame image is 0.746, with an average value of 0.49. Figure 18 [Figure 18: see original paper] shows observational samples from the image tracking system.

We collaborated with Yunnan Observatories to conduct high-resolution reconstruction based on observational data from the image tracking system. Using NASIR (Non-rigid Alignment based Solar Image Reconstruction) (Liu et al. 2022), we performed image reconstruction to obtain high-resolution images of the solar photosphere approaching the diffraction limit of AIMS (0.14 @550 nm). Figure 19 [Figure 19: see original paper] shows the high-resolution reconstructed image of NOAA AR 13719 on June 24, 2024, from image tracking system data, with MFGS = 0.9955.

3.4. Wide-band Imaging in 8-10 m

The 8-10 m imaging system can capture the umbra and penumbra of sunspots in the mid-infrared band. Figure 20(a) [Figure 20: see original paper] presents a set of observations from this system, while Figure 20(b) shows observations from the Helioseismic and Magnetic Imager (HMI) at a similar time. Noticeable brightening structures can be observed in regions surrounding the sunspot and corresponding to network magnetic fields. Simões et al. (2017) pointed out that the formation height of the infrared continuum is higher than that of the visible continuum, providing information about the upper photosphere. This explains the presence of brightening structures associated with network magnetic fields in the 8-10 m observations. Furthermore, their simulation results indicate that the formation height of the continuum can reach the chromosphere during flares. Previous examples of enhanced mid-infrared continuum radiation during flares have been reported (Penn et al. 2016). The pilot observation data from AIMS has captured multiple events of enhanced mid-infrared radiation during flares, providing data support for systematic studies of this phenomenon.

Currently, data processing software for the 8-10 m imaging system has been developed, primarily including dark field and flat field calibration. We have also attempted to use the AIMS 8-10 m imaging system for observations of non-solar targets. Figure 21 [Figure 21: see original paper] shows features of a lunar crater captured on August 18, 2024. In the future, we will attempt mid-infrared observations of some bright stars.

4. Summary and Discussion

After nearly a decade of effort, AIMS has completed all development work and conducted 15 months of scientific pilot observations. The results demonstrate that AIMS has achieved its core scientific goal, with magnetic field measurement accuracy better than 10 Gauss. Simultaneously, AIMS can perform rapid imaging observations in the 8-10 m range.

The method of directly measuring Zeeman splitting to obtain magnetic field strength, while significantly improving measurement accuracy, still faces difficulties in separating Zeeman sub-lines when observing weak magnetic fields. Thus, AIMS' s direct measurement method has limitations in its application scope. We have conducted simulation analyses on this (Li et al. 2021), and results show that, without considering noise, AIMS' s direct measurement method is effective for magnetic fields above 300 Gauss, meaning it can resolve three components. The left panel of Figure 22 [Figure 22: see original paper] shows results at transverse fields of 150, 300, and 450 G. The right panel shows an actual observation example, with a measured magnetic field strength of 440 Gauss, consistent with our simulation analysis. For weak magnetic fields below 300 Gauss, AIMS will revert to traditional mode, using polarization measurements and inversion to obtain magnetic field information. As mentioned earlier, although Zeeman splitting cannot be directly separated, the degree of splitting is still much greater than in the visible range, thus significantly improving measurement accuracy for weak magnetic fields.

Imaging is a very important observational capability for solar observations. Although AIMS is the first to achieve an imaging FTIR design internationally, and the measured spectral indicators all meet imaging requirements, the current array detector cannot fully meet the high-performance needs of FTIR. Therefore, AIMS currently only uses a 64 × 2 line array device, which limits AIMS' s full observational capabilities to some extent. In the future, we will continue to track technological advancements and seize opportunities to replace the current detector system with a larger array detector.

In solar magnetic field measurements, both measurement accuracy and spatial resolution are important indicators (Deng et al. 2009). Due to its long operating wavelength, AIMS has lower spatial resolution in its operating band compared to other advanced equipment. Although this does not affect achievement of AIMS' s core scientific goals, it remains a slight imperfection. AIMS' s optical design has considered this factor, retaining a visible light channel in the image tracking system of the Coudé room. In the future, we also consider upgrading this optical path and equipping it with necessary high-resolution observational terminals to enhance AIMS' s observational capabilities.

Polarization error plays a crucial role in measurement accuracy. Theoretically, additional telescope polarization is inversely proportional to wavelength. Therefore, achieving high-precision polarization measurements is easier in the mid-infrared band than in the visible band. In AIMS, we have significantly reduced telescope additional polarization by adopting an unpolarized derotator design. Systematic simulation results show that total instrumental polarization is below 0.003, and polarization crosstalk is below 0.02—one to two orders of magnitude lower than in the visible band. Nevertheless, future work will require more systematic polarization calibration and crosstalk correction for the AIMS telescope to obtain polarization signals with higher sensitivity.

During pilot observations, we conducted imaging observations of the Moon. In the future, we will also attempt to observe other celestial targets, such as large planets like Jupiter, and perform spectral observations of bright stars with strong magnetic fields.

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