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Polarization considerations in the multi-angle imager for aerosols (MAIA)

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ABSTRACT

The significant effects of aerosols on public health and climate drive a growing necessity for the characterization of particulate matter in air pollutants. The earth-orbiting Multi-Angle Imager for Aerosols (MAIA) instrument will combine radiance and polarization measurements to derive features of ground-level particulate matter. The optical design requires an in-depth analysis of several key polarization factors in order to meet stringent requirements on radiometric and polarimetric accuracy. A simple two-layer optical coating, a pair of achromatic quarter-wave plates, and analysis of the polarization aberrations are used to minimize the effects of polarization errors and achieve high polarimetric accuracy.

Keywords: aerosols, remote sensing, public health, polarization, quarter-wave plates

1. Introduction

Aerosols, tiny airborne particles, are a growing concern for public health and climate prediction. The complexity of aerosol composition and their variability in space and time complicates the task of measuring these particles. Ranging in size from 1 – 10 μm , aerosol particulate matter can result from the chemical interaction of elements present in the atmosphere or the addition of aerosol sources from the earth's surface into the atmosphere, such as dust, industrial emission, and biological waste¹.

In recent decades, the evidence of the negative health effects from exposure to air pollution has grown. A strong correlation exists between air pollution and health concerns such as premature death and respiratory disease. In 2012, an estimated 3.7 million deaths were associated with the ambient particulate matter in the atmosphere, making aerosol air pollutants the largest environmental health risk².

While in recent years numerous technological advancements have been made allowing for better measurement of surface-level particulate matter that humans are exposed to with instruments like the Multi-angle Imaging SpectroRadiometer (MISR) and Moderate resolution Imaging Spectroradiometer (MODIS), the missing piece to fully understanding the effects of aerosols on human health is particle composition.

2. MAIA Mission and Science Goals

The National Aeronautics and Space Administration (NASA) selected the Multi-Angle Imager for Aerosols (MAIA) as part of its Earth Venture Instrument program in March 2016³. In keeping with the larger goals of NASA and the science-driven goals of the Earth Venture missions, MAIA focuses on obtaining a better understanding of the earth's atmospheric makeup and its future effects on the human population by observing air pollution over major cities across the globe. These aerosol measurements will target respirable particulate matter (airborne particles with aerodynamic diameter < 10 microns or PM_{10}) and components of fine particulate matter (airborne particles with aerodynamic diameter < 2.5 microns or $\text{PM}_{2.5}$). Determining the composition of $\text{PM}_{2.5}$ and the associated properties is where current technology falls short for both ground stations and other satellite sensors.

MAIA's innovative design and data processing software will allow researchers to understand the toxicity and quantities of various components of $\text{PM}_{2.5}$, such as sulfate, nitrate, organic carbon, black carbon, and dust. Combining total PM_{10} ,

total $\text{PM}_{2.5}$, and $\text{PM}_{2.5}$ components with population health records, connections are seen between aerosol pollutants and health problems such as adverse birth outcomes, cardiovascular and respiratory diseases, and premature deaths.

The MAIA mission will collect data on aerosol pollutant size distribution, shape, and scattering properties. To achieve a higher sensitivity to particle size and composition at a moderately high spatial resolution of 1 km^4 , atmospherically scattered sunlight images are taken across the ultraviolet, visible, near-infrared, and shortwave-infrared spectra at multiple viewing angles while measuring the degree to which the scattered sunlight is polarized.

The primary target areas (PTAs) for the MAIA mission will be selected from a list of 11 potential candidates spanning five continents (Figure 1). During orbital operation, each PTA will be visited at least three times per week over the anticipated three-year mission period. Until a host is selected for the MAIA instrument, the exact target area size cannot be confirmed, however each PTA will fall within a square area of no less than $300 \text{ km} \times 300 \text{ km}$. The potential MAIA PTAs were selected to include major world population hubs with variety in the particulate matter concentrations and particle types present. Other criteria for PTA candidates includes access to ground-based sun photometers and chemical speciation monitors to validate the measurements from the MAIA instrument and readily available health data from the metropolitan areas targeted. Within each PTA, the particulate matter concentrations and compositions will be analyzed with respect to short-term exposure, chronic exposure, and maternal exposure to aerosols.

Figure 1. Global distribution of the Multi-Angle Imager for Aerosols (MAIA) potential primary target areas (PTAs).

While the MAIA mission's main goal is linking aerosol pollution to public health, the collaboration of many interdisciplinary teams composed of radiation, climate, and environmental scientists makes MAIA an ideal instrument for also studying the highest source regions of aerosols, the effect of air pollutants on cloud composition, and select environmental anomalies such as dust storms, wildfires, volcanic eruptions, and hurricanes. Compiled data will also be used to assess the accuracy of climate and forecast models. It is expected that data will be made available to interested researchers within two days of a given PTA observation.

3. MAIA Optical Design

The MAIA instrument will allow for the derivation of characteristics and abundances of ground-level particulate matter by measuring the radiance and polarization of scattered sunlight from atmospheric aerosols. This integrated imaging device combines multispectral, multiangular, and polarimetric imaging technology into one system, able to achieve spectral coverage from the ultraviolet (UV) to the shortwave infrared (SWIR)

Two pushbroom spectropolarimetric cameras (Figure 2a) mounted on a two-axis gimbal provide multiangle viewing capabilities of the earth target locations. The scan (along-track, with field of regard ± 60 degrees) axis uses a "step and

stare” observation method to provide multi-angle viewing of PTAs. The pan (cross-track, with field of regard ± 45 degrees) axis allows for observation of PTAs that do not fall directly on the subspacecraft path (Figure 2b).

Figure 2. The MAIA instrument data acquisition strategy. A) Early conceptual configuration of the MAIA instrument. B) The scan gimbal axis allows for multiangle images of the PTAs, while the pan gimbal axis provides the mission with higher revisit frequency for PTAs.

The fourteen-band (365, 385, 415, 442, 550, 645, 749, 762.5, 867, 945, 1038, 1610, 1880, and 2125 nm) camera system measures polarization at 442 nm, 645 nm, and 1038 nm. The MAIA instrument’s sensitivity to aerosols is enhanced by the combination of polarimetric and radiometric measurements. To achieve the precision necessary to distinguish characteristics and toxicity levels of $PM_{2.5}$ components, a degree of linear polarization (DoLP) accuracy of 0.005 is required for the retrieval of aerosol refractive index data.

The four-mirror, reflective, anastigmatic telescope (Figure 3) has a 61 mm effective focal length. The system stop is located between the secondary and tertiary mirrors, and in this region rays from any point in the field of view are nearly collimated. Here, a symmetric set of quarter wave plates (QWPs) and photoelastic modulators (PEMs) together act as a circular retarder.

Figure 3. The MAIA optical design shows the primary and secondary mirrors directing scattered sunlight through the polarization modulator optics (QWPs 1 and 2, PEMs 1 and 2). The modulated polarization signal is then reflected from the tertiary and quaternary mirrors to the analyzer wiregrid polarizers attached to the detector.

PEMs exhibit time-varying retardance by inducing stress birefringence with a driving sound wave with the uniaxial crystal's natural frequency. Typical PEM frequencies are on the order of the tens of kilohertz. Such frequencies are significantly larger than the modulation frequency required by MAIA of ~ 27.5 Hz. For this reason, the dual-PEM method, used in early iterations of aerosol-detecting satellites like MSPI⁵, is desirable for the MAIA instrument as well. Operating a pair of PEMs in series with slightly different frequencies results in a retardance modulation with a high-frequency carrier wavefront modulated by the smaller beat frequency. The combination allows for a sampling of the beat frequency's waveform while averaging out the high-frequency carrier signal.

4. Polarization Considerations

Polarization errors in the MAIA instrument can arise from the surface geometry of the optical components, thin-film coatings, and the QWPs. With the 0.005 DoLP uncertainty requirement, every aspect of the optical design must be analyzed to understand the effects of polarization properties that arise from each component. An optical coating was designed for the four telescope mirrors, eliminating excess retardance caused by each reflection. The design and fabrication process of the three-component, achromatic, athermal QWPs were modeled to reduce the retardance magnitude and orientation errors that result mainly from the uncertainty of the individual crystal's birefringence.

4.1 Reduced-retardance telescope mirror coating

Due to the high precision necessary in the polarization measurements to distinguish between different aerosol sizes and components, a simple retardance-reducing optical coating was designed to minimize the polarization aberrations from the series of reflections. A simple coating that balanced performance, fabrication process, and cost was desirable. Angles of incidence (AOIs) on each of the four mirrors will range from 0 to 33 degrees. Because polarization errors tend to increase with angle of incidence, specifications put on diattenuation and retardance were analyzed at the maximum AOI. Target specifications for the telescopic mirror coatings are listed in Table 1.

Table 1. Desired reflectance, diattenuation, and retardance performance for MAIA telescope mirror coating.

Mirror Coating Performance Specifications	
Reflectance	$R > 0.95$
Diattenuation at 33°	$D < 0.02$ radians
Retardance at 33°	$\delta < 0.03$ radians

Bare aluminum, while highly reflective and proven qualified for space flight, introduces a significant amount of polarization error (Figure 4). The addition of a simple optical coating can reduce these polarization aberrations and improve the performance of the telescope system.

Figure 4. Contour plots of bare aluminum diattenuation and retardance as functions of angle of incidence (0 – 35 degrees) and wavelength (0.3 - 2.25 microns). Both diattenuation and retardance values are in radians.

Several coating prescriptions were designed and analyzed for implementation on the MAIA telescope mirrors. Working with space-qualified materials, the tested coatings consisted of magnesium fluoride (MgF_2), hafnium dioxide (HfO_2) and aluminum oxide (Al_2O_3). Single-layer, two-layer, and four-layer coatings were modeled in the Mathematica-based polarization optical design software, Polaris-M.

Each coating was adjusted to minimize the retardance in both the full wavelength and full angle of incidence ranges. The single-layer of MgF_2 on aluminum was selected and further optimized with a thickness of $27.5 \text{ nm} \pm 10\%$. Relative to a bare aluminum substrate, the reflectance is nearly unchanged but the diattenuation and retardance are decreased (Figure 5). Without a significantly more complex coating, the absorption band of aluminum (810 – 820 nm) remains a minimum in the reflectance spectrum with $R=0.866$, however cost and ease of fabrication were deciding factors to move forward with a lower reflectance coating than initially specified.

Figure 5. Plots of reflectance, diattenuation, and retardance show the performance of the reduced-retardance telescope mirror coating for the MAIA camera system. The nominal MgF_2 thickness value (27.5 nm) and the upper (30.25 nm) and lower (24.75) thickness tolerances are plotted in comparison to a bare aluminum substrate.

Because the three polarimetric bands (centered at 442, 645, and 1038 nm) are where polarization measurements are taken, minimizing the diattenuation and retardance at these wavelengths is crucial. The behavior of the polarimetric wavelengths as functions of the angle of incidence are found in Figure 6, which provides more insight into the diattenuation and retardance trends for each band.

Figure 6. Plots of diattenuation and retardance versus angle of incidence for the three central wavelengths of the polarimetric bands show how the polarization properties depend on wavelength and meet the desired performance specifications.

4.2 Achromatic quarter wave plate design

The MAIA camera system requires a pair of achromatic, athermal quarter wave plates (QWPs) made from three crystalline materials: quartz, magnesium fluoride (MgF₂) and sapphire. Due to the uncertainty in the birefringence of each material, fabricating these QWPs with only a thickness specification is nearly impossible. Utilizing methods from previous work⁵, the MAIA QWPs will be fabricated using a method developed with Karl Lambrecht Corporation in which the retardance of each material is monitored during the polishing process to ensure limited polarization errors.

The QWPs are required to have a retardance of 90° ± 10° over each of the three polarimetric wavebands (Table 2) and the During fabrication, a number of variables could result in extra retardance error. The sapphire and quartz fast axes must be aligned perpendicular to the MgF₂ fast axis within 10 arcminutes. The fast axis of each of the three crystals must be parallel to the polished surfaces within 15 arcminutes. The wedge in a polished crystal must be less than 1 arcsecond. The surface power of the polished crystal must be less than 0.005 m⁻¹. Finally, the wedge in the fully assembled QWP due to the adhesive must be less than 2 arcminutes.

Table 2. The three polarimetric bands of the MAIA instrument. Typically, the bands are referred to by the central wavelength, but for the performance analysis of the QWPs, the minimum and maximum wavelengths must also meet the retardance requirement.

Central Wavelength	FWHM	Minimum Wavelength	Maximum Wavelength
442 nm	56 nm	414 nm	470 nm
645 nm	74 nm	608 nm	682 nm
1038 nm	97 nm	989.5 nm	1086.5 nm

A design for the QWP was developed utilizing the birefringence and thermo-optic coefficients of the quartz, MgF₂, and sapphire to create an athermal and achromatic element. Nominal thickness values are provided to the vendors as an initial guideline but these can be adjusted during the fabrication process depending on the retardance values measured during polishing. The QWPs designed for the MAIA instrument will have a 676.721 μm quartz crystal, followed by a 202.077 μm MgF₂ crystal, and ending with a 485.645 μm sapphire crystal. These thickness values were used during modeling and simulations as the “ideal” QWP and resulted in the “ideal” retardance values for the three polarimetric wavebands. At the central wavelengths (442, 645, 1038 nm), the QWP produces retardances of 89.6°, 96.4°, and 87.1°, respectively.

A sensitivity analysis was performed to understand the change in the retardance as a result of the above vendor-provided and design-required tolerances on the variable parameters in the QWP fabrication. Tables 4-6 give the data for the three most sensitive design parameters: material thickness, individual crystal wedge, and surface power. The tolerance listed is the change made to the “ideal” design during the simulation, and the retardance error is the change from the “ideal” retardance values for each central wavelength.

Table 4. Sensitivity analysis results for a $\pm 0.5 \mu\text{m}$ change in material thickness.

Material	Central Wavelength	Tolerance	Retardance Error
Quartz	442 nm	$\pm 0.5 \mu\text{m}$	3.96°
	645 nm	$\pm 0.5 \mu\text{m}$	2.62°
	1038 nm	$\pm 0.5 \mu\text{m}$	1.56°
MgF ₂	442 nm	$\pm 0.5 \mu\text{m}$	5.04°
	645 nm	$\pm 0.5 \mu\text{m}$	3.41°
	1038 nm	$\pm 0.5 \mu\text{m}$	2.07°
Sapphire	442 nm	$\pm 0.5 \mu\text{m}$	3.51°
	645 nm	$\pm 0.5 \mu\text{m}$	2.33°
	1038 nm	$\pm 0.5 \mu\text{m}$	1.41°

Table 5. Sensitivity analysis results for a $\pm 0.005 \text{ m}^{-1}$ change in surface power.

Material	Central Wavelength	Tolerance	Retardance Error
Quartz	442 nm	$\pm 0.005 \text{ m}^{-1}$	2.36°
	645 nm	$\pm 0.005 \text{ m}^{-1}$	3.57°
	1038 nm	$\pm 0.005 \text{ m}^{-1}$	1.35°
MgF ₂	442 nm	$\pm 0.005 \text{ m}^{-1}$	3.21°
	645 nm	$\pm 0.005 \text{ m}^{-1}$	4.03°
	1038 nm	$\pm 0.005 \text{ m}^{-1}$	2.26°
Sapphire	442 nm	$\pm 0.005 \text{ m}^{-1}$	1.80°
	645 nm	$\pm 0.005 \text{ m}^{-1}$	2.50°
	1038 nm	$\pm 0.005 \text{ m}^{-1}$	1.51°

Table 6. Sensitivity analysis results for a ± 1 arcsecond change in crystal wedge.

Material	Central Wavelength	Tolerance	Retardance Error
Quartz	442 nm	± 1 arcsecond	2.46°
	645 nm	± 1 arcsecond	1.60°
	1038 nm	± 1 arcsecond	0.46°
MgF ₂	442 nm	± 1 arcsecond	2.09°
	645 nm	± 1 arcsecond	1.80°
	1038 nm	± 1 arcsecond	1.18°
Sapphire	442 nm	± 1 arcsecond	1.83°
	645 nm	± 1 arcsecond	1.57°
	1038 nm	± 1 arcsecond	0.88°

A Monte Carlo simulation was performed to determine the fabrication accuracy given the vendor-provided tolerances from the sensitivity analysis. Each variable was assumed to have a truncated Gaussian distribution with a mean equal to the nominal value of the variable and a 2σ value equal to the design tolerances (Table 7). Trials in which a variable's value was outside of the 2σ range were eliminated. For a trial to “pass”, the retardance at the lower and upper wavelength of each polarimetric band must be $80^\circ \leq \delta \leq 100^\circ$ when averaged over the field of view.

Table 7. The breakdown of mean and standard deviation values for each variable in the Monte Carlo simulation to test QWP performance.

Parameter	Average Value (μ)	Standard Deviation (σ)
Quartz thickness	676.721 μm	0.25 μm
MgF ₂ thickness	202.077 μm	0.25 μm
Sapphire thickness	485.645 μm	0.25 μm
Material wedge	0 arcseconds	0.5 arcseconds
Surface power (1/R)	0 m^{-1}	0.0025 m^{-1}
Fast-axis tilt	0 arcminutes	7.5 arcminutes
Axis alignment	0 arcminutes	5 arcminutes
Assembly wedge	0 arcminutes	1 arcminute

A total of 200 successful (no values outside of 2σ range) simulations were performed. 188 simulations passed, resulting in a 94% success rate and providing confidence that the given design will provide acceptable QWPs to use for the space flight camera systems.

A series of other models were run to determine the best angular tilt of the QWPs in the camera system. Initial designs had a 7.5 degree tilt about the x-axis in opposite directions for QWP1 and QWP2, however it was found that ghosting on the detector would be minimized if the QWPs were aligned differently. The configuration with a 10.9 degree tilt about the y-axis in opposite directions both minimized ghosting and improved the performance of the QWP retardance spectrum in the outer field of view regions.

5. Conclusions and Future Work

Further analysis of the polarization errors relevant to the MAIA instrument is being completed. A first-order, on-axis Mueller matrix model of the camera optical system will be the first step to completing a full polarization ray tracing analysis. The polarization ray trace of MAIA's optics will be used to determine the c and d calibration coefficients that are necessary to accurately program the on-board calibrator and retrieve aerosol composition and abundance data.

The MAIA instrument launch date is dependent on the host satellite and is anticipated to be scheduled in the early 2020s.

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