Impacts of Optical Coatings on Polarization and Coronagraphy

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The LUVOIR mission's exoplanet science objectives require high-contrast imaging with an internal coronagraph. A coronagraph's wavefront control system uses deformable mirrors to correct amplitude and wavefront aberrations in the optical system, allowing the diffracted starlight to be suppressed so that orbiting exoplanets can be directly observed. Metallic coatings that are typically used on mirror surfaces present a challenge for a coronagraph's wavefront control system. Specifically, the orthogonal polarization states of light (often denoted by "*s*" and "*p*") are affected differently by the coating, as a function of wavelength, angle of incidence, and coating properties.

There are two effects of concern. The first effect is polarization aberration, where each polarization state sees a different amplitude (*diattenuation*) and phase change (*retardance*) upon reflecting from a metallic surface (see Figure 1). The second is cross-polarization leakage, where some portion of a polarization state is converted into the orthogonal state upon reflection. The result of these two effects is that when unpolarized light (such as starlight) reflects from a metallic surface, four independent (or incoherent) electric fields are created: *s*-incident light reflected in the *s*-state ("*ss*"), *s*-incident light reflected in the *p*-state ("*sp*"), *p*-incident light reflected in the *p*-state ("*pp*"), and *p*-incident light reflected in the *s*-state ("*ps*"). Since these fields are incoherent (i.e. they have uncorrelated amplitude and spatial variations), a coronagraph can only control and correct for one of these fields at a time. Thus, if the wavefront control system is sensing and correcting the amplitude and wavefront aberrations of the *ss* electric field, the other three fields will contribute to leaked starlight that could potentially obscure an exoplanet. It is important to note that the cross-polarization terms (*sp* and *ps*) are orders of magnitude smaller than the primary terms (*ss* and *pp*)[1].

There are several ways to address the polarization issues:

Telescope Design Considerations: Both effects are strongly dependent on the angle-of-incidence (AOI) of the light at the optical surface. Slower (high-F/#) optics will have lower AOIs across the surface of the mirrors, thus minimizing the polarization effects. Flat mirrors that are used to fold the optical path at large angles should also be avoided, or used in pairs such that the effects are cancelled out. Slower optics, however, can lead to longer optical systems with smaller fields-of-view. The impacts of polarization aberration and cross-polarization leakage must therefore be traded against volume constraints and science objectives.

Coating Properties: The polarization effects are also dependent on the coating properties, specifically the index of refraction; choosing appropriate materials can help minimize the effects. To enable the LUVOIR mission's ultraviolet (UV) science objectives requires a protected aluminum coating on at least the primary and secondary mirrors. It is expected that there is little that can be done from a coating perspective to further reduce the polarization effects, aside from ensuring that the protective overcoat material does not significantly increase the effects over the base aluminum layer.

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[1] See K. Balasubramanian, *et al.*, Proc. SPIE **8151**, 81511G (2011) for additional details.

Coronagraph Architecture: Perhaps the most effective way to deal with polarization aberrations is to split the light at the coronagraph and only observe one polarization at a time. This can be done serially by a single instrument: A polarized filter would select a single polarization state for which the aberrations would be sensed and observed, allowing for exoplanet detection and correction in that polarization state; the orthogonal polarization state could then be selected and the observation repeated. This approach is similar to that adopted by the WFIRST coronagraph instrument, but has the drawback of requiring twice the amount of time to capture all of the exoplanet photons. Alternatively, the polarization states can be split with a polarizing beam-splitter, with each being sent to a separate coronagraph instrument. This allows for simultaneous observation of all of the exoplanet photons, at the expense of requiring two coronagraph instruments, each with its own focal plane, filter wheels, deformable mirrors, and associated electronics. An additional avenue of research includes introducing polarization-controlling diffractive optical elements to correct the effects.

Regardless of the approach taken, there are two key questions that remain to be answered. The first question is how effective are polarizing filters or polarizing beam-splitters at separating the orthogonal states. Achieving 10^{-10} raw contrast may require polarizing optical components that are beyond the state-of-the-art. The second question regards the cross-polarization leakage term. When a single polarization state is selected (say, s), both the ss and ps components are transmitted. If the coronagraph wavefront control system senses and corrects the ss component, then the ps component will contribute a low-level static speckle background that may obscure an exoplanet. Modeling must be performed on a LUVOIR-relevant architecture to fully understand the magnitude of the cross-polarization terms and if they are significant enough to be of concern. If they are, additional post-processing steps may need to be taken to calibrate these terms out.

It is important to note that coating-induced polarization aberration and cross-polarization leakage will be generated by ***any*** metallic mirror coating. Figure 2 shows the diattenuation and retardance for both a bare aluminum-coated and bare silver-coated mirror. Both aluminum and silver have similar order-of-magnitude effects. ***It is therefore a false assumption to believe that high-contrast coronagraphy performance can be significantly improved by switching from an aluminum coating to a silver coating.***

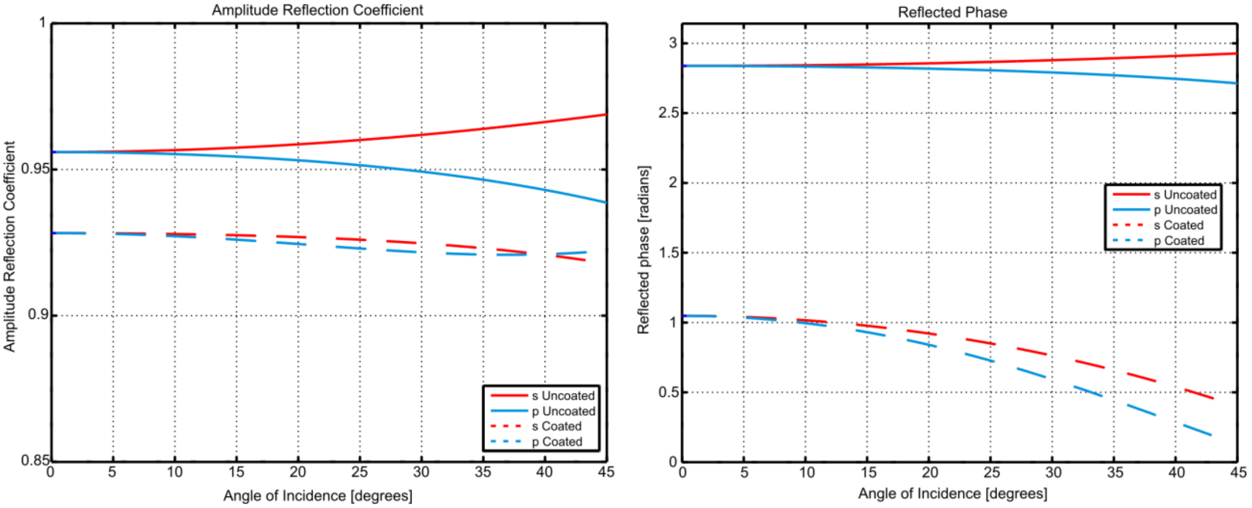

Figure 1 – ***Left:*** **Amplitude reflection coefficient for each polarization state as a function of angle of incidence for a bare aluminum mirror (*solid lines*) and an aluminum mirror coated with a quarter-wave of MgF_2 (*dashed lines*) at a wavelength of 550 nm.** ***Right*****: The reflected phase shift for the same two cases. In each case, the orthogonal polarization states experience a different amplitude and phase change upon reflection. Angles of incidence at the primary and secondary mirrors for an on-axis, 12-m-class telescope would typically be less than 15 degrees.**

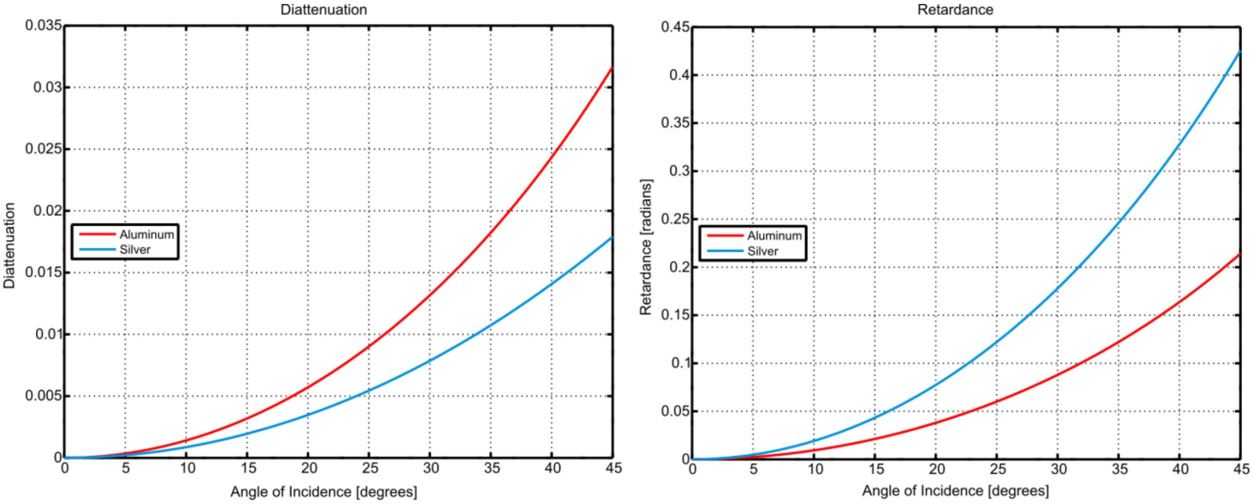

Figure 2 – ***Left:*** **The diattenuation (normalized reflected amplitude difference between polarization states) as a function of angle of incidence for bare aluminum and bare silver coatings at a wavelength of 550 nm.** ***Right:*** **The retardance (absolute reflected phase difference between polarization states) as a function of angle of incidence for the same two metals. Angles of incidence at the primary and secondary mirrors for an on-axis, 12-m-class telescope would typically be less than 15 degrees.**