UV Coatings, Polarization, and Coronagraphy

Matthew R. Bolcar, Manuel Quijada, Garrett West (GSFC)
Bala Balasubramanian, John Krist, Stefan Martin (JPL)
Derek Sabatke (BATC)
Objectives

• Review of UV coatings and state-of-the-art

• Review of polarization aberration and the impact on coronagraphy

• Recent study results
  • HabEx
  • LUVOIR

• Work to be done
Objectives

• Review of UV coatings and state-of-the-art

• Review of polarization aberration and the impact on coronagraphy

• Recent study results
  • HabEx
  • LUVOIR

• Work to be done
UV Coatings

• Sensitivity in the UV requires aluminum-coated mirrors
UV Coatings

• Sensitivity in the UV requires aluminum-coated mirrors

• Aluminum oxidizes nearly instantly upon exposure to air (even at very low pressures)
  • Oxidation layer reduces UV reflectivity
UV Coatings

• Sensitivity in the UV requires aluminum-coated mirrors

• Aluminum oxidizes nearly instantly upon exposure to air (even at very low pressures)
  • Oxidation layer reduces UV reflectivity

• Protective overcoats are used to prevent oxidation
  • Commonly fluoride overcoats, such as MgF₂, LiF, or AlF₃
  • Provide high reflectivity for wavelengths as short as ~110 nm
  • Shortward of 110 nm, reflectivity depends on material and deposition process
UV Coatings

- **Al + MgF$_2$**
  - New “hot” deposition process heats substrate to 220° C
  - Improved reflectivity (> 85%) above 120 nm
  - Cutoff occurs around 115 nm with limited reflectivity shortward
    - ~20% reflectivity at 100 nm

- **Al + LiF**
  - Lower cutoff than MgF$_2$, achieving 80% reflectivity as low as ~105 nm
  - LiF is hygroscopic
    - Performance degrades with exposure to water vapor in air
    - Would require dry purge on mirrors during ground operations, OR
    - Requires an additional protective overcoat which can further suppress reflectivity

- **Al + AlF$_3$**
  - Promising new coating with low cutoff like LiF, and stability of MgF$_2$
UV Coatings

![Graph showing reflectivity versus wavelength for UV Coatings.](image)
UV Coatings

![Graph showing reflectivity vs. wavelength for different coatings.](graph.png)
UV Coatings

Reflectivity [%]

Wavelength [nm]

Bare Al
Al+MgF₂
Al+LiF

80 100 120 140 160 180 200
0 10 20 30 40 50 60 70 80 90 100

UV Coatings, Polarization, and Coronagraphy
UV Coatings

![Graph showing reflectivity vs wavelength for different coatings]

- **Bare Al**
- **Al+MgF₂**
- **Al+LiF**
- **Al+LiF+AlF₃**

*UV Coatings, Polarization, and Coronagraphy*
UV Coatings

![Graph showing reflectivity vs. wavelength for different UV coatings.](image-url)
Objectives

• Review of UV coatings and state-of-the-art

• Review of polarization aberration and the impact on coronagraphy

• Recent study results
  • HabEx
  • LUVOIR

• Work to be done
How Coatings Affect Polarization

- Terminology:
  - *Diattenuation*: when each polarization state see a different amplitude upon reflection
  - *Retardance*: when each polarization state sees a different phase upon reflection
How Coatings Affect Polarization

• There are two *mechanisms* of affecting the polarization-dependent amplitude and phase

• *Polarization Aberration:*
  • Each polarization state acquires a different amplitude and wavefront error as it traverses the system

• *Cross-polarization Leakage:*
  • Some of each polarization state “leaks” into the orthogonal polarization state

• Net result is *four* incoherent (i.e. independent, uncorrelated) electric fields that must be corrected by the coronagraph
Example:

\[ E = \begin{pmatrix} E_x \\ E_y \end{pmatrix} \]

Primary Mirror \rightarrow Secondary Mirror \rightarrow Coronagraph Optics \rightarrow Detector

\[ E = \begin{pmatrix} E_{xx} & E_{yx} \\ E_{xy} & E_{yy} \end{pmatrix} \]
Example:

\[ E = \begin{pmatrix} E_x \\ E_y \end{pmatrix} \]

- Primary Mirror
- Secondary Mirror
- Coronagraph Optics
- Detector

\[ E = \begin{pmatrix} E_{xx} & E_{yx} \\ E_{xy} & E_{yy} \end{pmatrix} \]

Polarization Aberration Terms
Cross-polarization Leakage Terms

Example:

\[ E = \begin{bmatrix} E_s \\ E_p \end{bmatrix} \]

Primary Mirror \[\rightarrow\] Secondary Mirror \[\rightarrow\] Coronagraph Optics \[\rightarrow\] Detector

\[ E = \begin{bmatrix} E_{xx} & E_{yx} \\ E_{xy} & E_{yy} \end{bmatrix} \]

Cross-polarization Leakage Terms
Example:

\[
E = \begin{pmatrix} E_x \\ E_y \end{pmatrix}
\]

- Four incoherent (uncorrelated), aberrated fields
- If we do nothing:
  - Coronagraph senses and corrects the average electric field
  - Uncorrected portion contributes to contrast leakage
Potential Solution #1:

\[ E = \left\{ \frac{E_x}{E_y} \right\} \]

- Filter polarization at detector plane
- Image is constructed of only “x” polarization components
- Again, coronagraph senses and corrects the average of the remaining terms
- \( E_{xx} \gg E_{yx} \) so we get good, but imperfect correction
- But you lose 50% of the light at the detector

\[ E = \begin{pmatrix} E_{xx} & E_{yx} \\ E_{xy} & E_{yy} \end{pmatrix} \]
Potential Solution #2:

\[ E = \begin{bmatrix} E_x \\ E_y \end{bmatrix} \]

- Split polarizations before entering separate coronagraphs
- Still sensing average of primary and cross-polarization fields, so correction is good, but imperfect
- Retain 100% of the light
- Requires 2x coronagraphs (2x optics, 2x detectors, 2x DMs)
Other Mitigation Strategies

• Limit angles-of-incidence (AOI):
  • Slower primary and secondary mirror F/#’s
  • Avoid flat-fold mirrors at high AOI
    • Can be used in “crossed-pairs” to cancel each other out
  • Creates “long” optical systems which makes packaging and stability difficult
Other Mitigation Strategies

• Limit angles-of-incidence (AOI):
  • Slower primary and secondary mirror F/#’s
  • Avoid flat-fold mirrors at high AOI
    • Can be used in “crossed-pairs” to cancel each other out
    • Creates “long” optical systems which makes packaging and stability difficult

• Optimize coatings:
  • Simultaneously optimizing coating properties/prescription with the optical design can minimize polarization aberration effects
Other Mitigation Strategies

• Limit angles-of-incidence (AOI):
  • Slower primary and secondary mirror F/#’s
  • Avoid flat-fold mirrors at high AOI
    • Can be used in “crossed-pairs” to cancel each other out
    • Creates “long” optical systems which makes packaging and stability difficult

• Optimize coatings:
  • Simultaneously optimizing coating properties/prescription with the optical design can minimize polarization aberration effects

• Polarization compensating components:
  • Investigate active or passive devices that may be able to compensate polarization aberrations
    • Liquid crystals, nonlinear devices, etc.
Objectives

• Review of UV coatings and state-of-the-art

• Review of polarization aberration and the impact on coronagraphy

• Recent study results
  • HabEx
  • LUVOIR

• Work to be done
HabEx Polarization Study

• Design based on Exo-C Telescope resized from 1.4 m to 4.0 m diameter

• Telescope is an off-axis, unobscured Ritchey-Chretien design

• Produced a family of designs with primary mirror F#s of 2.5, 2.0, 1.5, 1.25

• For analysis, polarization wavefront analyzed from primary mirror to DM1

• Two scenarios:
  • Coatings on PM, SM, TM are aluminum, with silver on rest of optics, OR
  • All mirrors are silver
Four designs, Primary F#s 2.5, 2.0, 1.5 and 1.25
HabEx: X-Y Polarization Wavefront Differences, f/2.5

X-Y Phase

445 nm  550 nm  650 nm  750 nm  850 nm  950 nm

Al, Ag
Ag

X-Y Phase (tilt removed)

445 nm  550 nm  650 nm  750 nm  850 nm  950 nm

Al, Ag
Ag

X-Y Amplitude

445 nm  550 nm  650 nm  750 nm  850 nm  950 nm

Al, Ag
Ag

Tilt & astigmatism are the main polarization aberrations
HLC: Post-EFC Contrast: 400-490 nm
All polarizations

No polarization errors
**HLC**: Post-EFC Contrast: 720-880 nm

All polarizations

![Graph showing mean azimuthal contrast vs. \( \lambda/D \) for different aperture sizes and material compositions.](image)
One Line Summary (courtesy J. Krist):

“Use overcoated Aluminum on the 1st three optics.”
LUVOIR Polarization Study

• Four Ritchey-Chretien telescope designs generated:
  • 9m, 12m, 16m on-axis
  • 9m off-axis

• All designs have:
  • 3x3 arcmin diffraction-limited field-of-view
  • Same Primary-to-Secondary Mirror separation
  • Same focal length and hence same plate scale (pixel size on sky)
  • Aluminum-coated mirrors

• Primary mirror F/# varies with design:
  • F/1.1 for 16-m
  • F/1.45 for 12-m
  • F/1.95 for 9-m on-axis
  • F/1.96 for 9-m off-axis
LUVOIR Designs

9-m, F/1.95
Max AOI: 8.51°

12-m, F/1.45
Max AOI: 11.43°

16-m, F/1.1
Max AOI: 15.1°

9-m, F/1.96
Max AOI: 20.26°
LUVOIR Study is Ongoing

- Preliminary polarization aberration result is available for a single scenario:
  - 12-m on-axis design (F/1.45) at a wavelength of 1 µm
LUVOIR Study is Ongoing

- Preliminary polarization aberration result is available for a single scenario:
  - 12-m on-axis design (F/1.45) at a wavelength of 1 µm
LUVOIR Study is Ongoing

- Preliminary polarization aberration result is available for a single scenario:
  - 12-m on-axis design (F/1.45) at a wavelength of 1 µm
Objectives

• Review of UV coatings and state-of-the-art

• Review of polarization aberration and the impact on coronagraphy

• Recent study results
  • HabEx
  • LUVOIR

• Work to be done
Work to Be Done

• LUVOIR needs to complete analysis of other designs and perform propagation through coronagraph
  • Of specific interest is the on- vs. off-axis trade
Work to Be Done

• LUVOIR needs to complete analysis of other designs and perform propagation through coronagraph
  • Of specific interest is the on- vs. off-axis trade

• Both studies should improve fidelity of coating models
  • Hubble Al+MgF$_2$ was used for HabEx, and Al+SiO$_2$ was used for LUVOIR
  • Update with newer MgF$_2$, LiF, or AlF$_3$ coating information
Work to Be Done

• LUVOIR needs to complete analysis of other designs and perform propagation through coronagraph
  • Of specific interest is the on- vs. off-axis trade

• Both studies should improve fidelity of coating models
  • Hubble Al+MgF₂ was used for HabEx, and Al+SiO₂ was used for LUVOIR
  • Update with newer MgF₂, LiF, or AlF₃ coating information

• Investigate optimizing coatings to balance/minimize polarization aberration
Work to Be Done

• LUVOIR needs to complete analysis of other designs and perform propagation through coronagraph
  • Of specific interest is the on- vs. off-axis trade

• Both studies should improve fidelity of coating models
  • Hubble Al+MgF$_2$ was used for HabEx, and Al+SiO$_2$ was used for LUVOIR
  • Update with newer MgF$_2$, LiF, or AlF$_3$ coating information

• Investigate optimizing coatings to balance/minimize polarization aberration

• If different coronagraph channels will be used to process each polarization orientation separately, need to understand impact of cross-polarization leakage
Summary

• Recent protected-Al coatings deliver high-reflectivity down to 110 nm
  • Performance below 110 nm depends on prescription and deposition processes
Summary

• Recent protected-Al coatings deliver high-reflectivity down to 110 nm
  • Performance below 110 nm depends on prescription and deposition processes

• Both LUVOIR & HabEx are pursuing parametric studies to understand trades with respect to telescope aperture and design
Summary

• Recent protected-Al coatings deliver high-reflectivity down to 110 nm
  • Performance below 110 nm depends on prescription and deposition processes

• Both LUVOIR & HabEx are pursuing parametric studies to understand trades with respect to telescope aperture and design

• HabEx study shows aluminum coating appears to be better than, or approximately equivalent to, silver coating with respect to polarization