Mirror Coatings for large aperture UV to IR Telescopes

Bala K. Balasubramanian
Jet Propulsion Laboratory
California Institute of Technology

HabEx Technology Meeting
3 August 2016
Jet Propulsion Laboratory

Requirements and Challenges

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- UV Optical IR telescope optics covering FUV to NIR
- High Reflectance including the far UV down to 90nm
- Large area, meter class optics
- High Uniformity
- Polarization
- Stability in the environment, robust protection

High Reflectivity Metals

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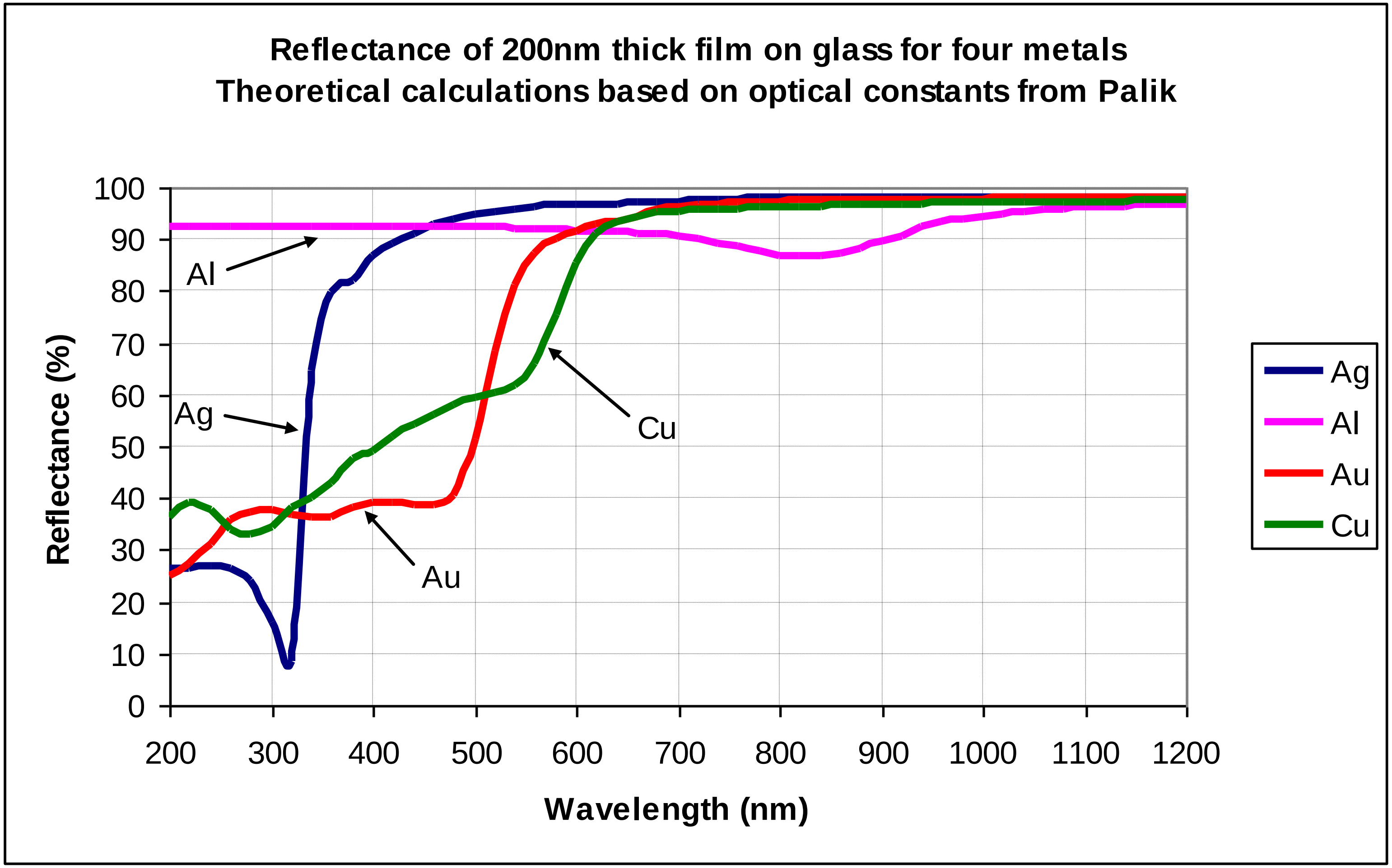


Aluminum is the obvious choice

Technical Challenges

Performance impact due to:

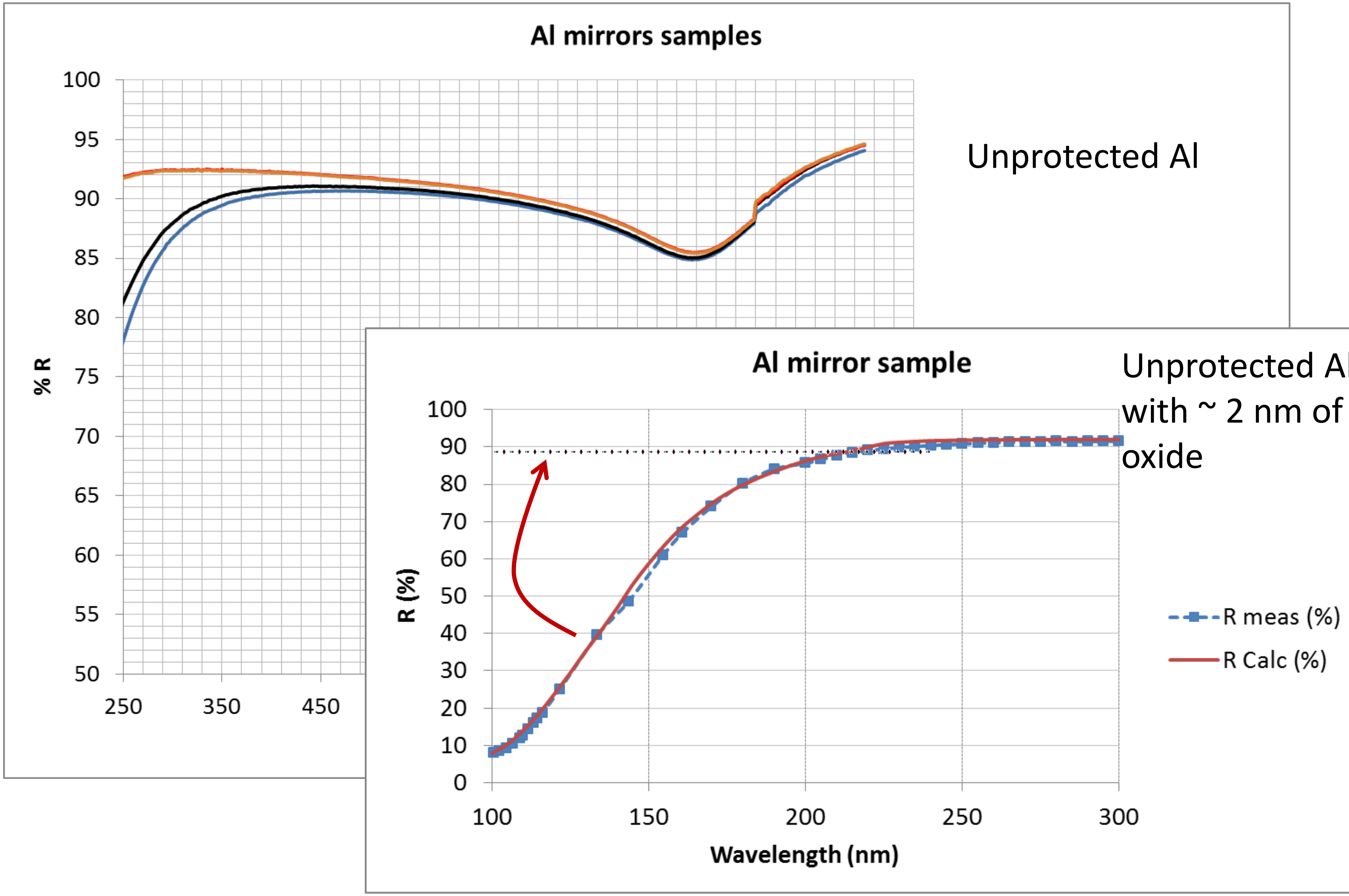
1. Chemical (contamination, oxidation, stoichiometry)
   - Absorption
   - Instability/durability

2. Microstructural
   - Scattering
   - Water vapor adsorption

3. Uniformity over large area

4. Polarization sensitivity

Unprotected Aluminum Mirror



Unprotected Aluminum

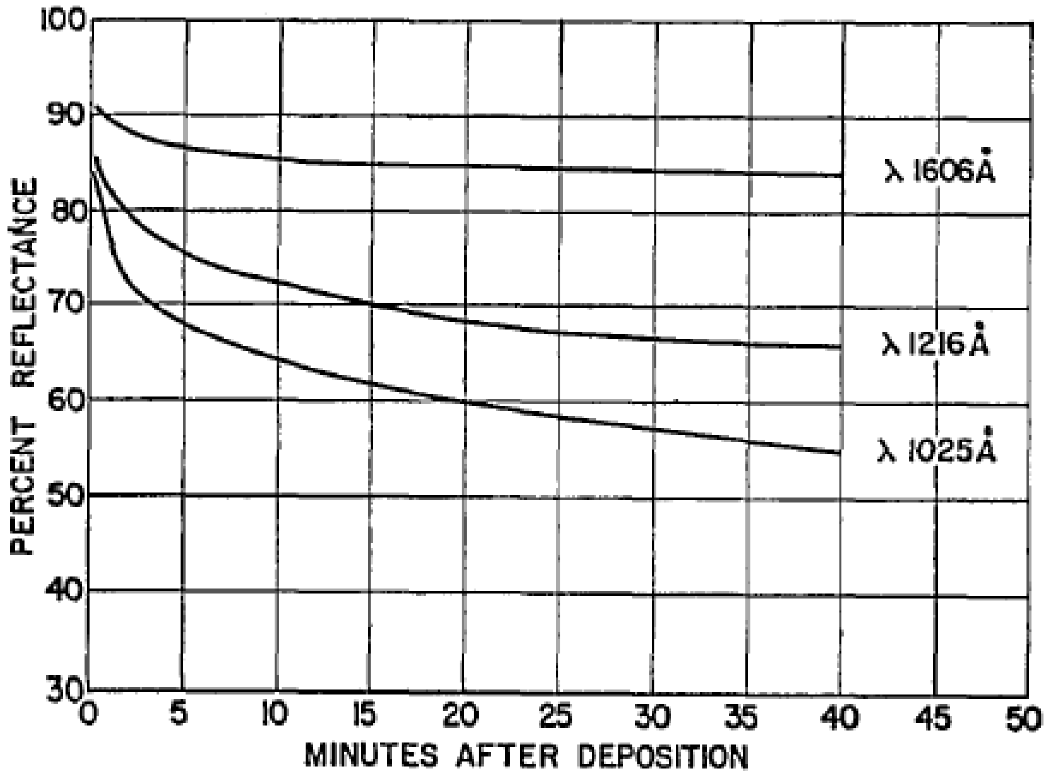
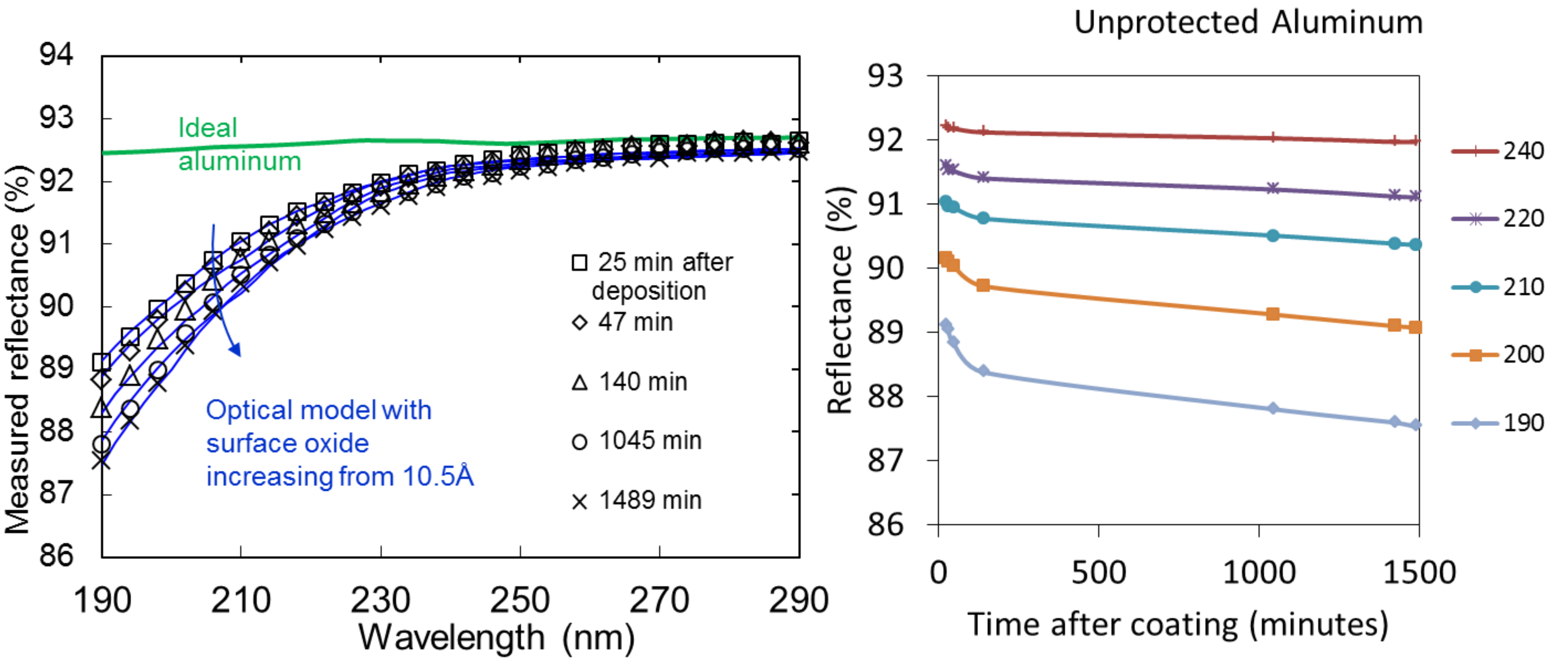


FIG. 4. Reflectance decrease of freshly deposited aluminum films in vacuum at three wavelengths in the vacuum ultraviolet as a function of time up to 40 min.

On the Vacuum-Ultraviolet Reflectance of Evaporated Aluminum before and during Oxidation*

R. P. MADDEN, L. R. CANFIELD, AND G. HASS; JOSA Vol:53 No:5, May 1963

Unprotected Aluminum



Oxidation induced reflectance reduction in the near UV of an Al mirror sample; Models predictions match a progressive increase of oxide formation.

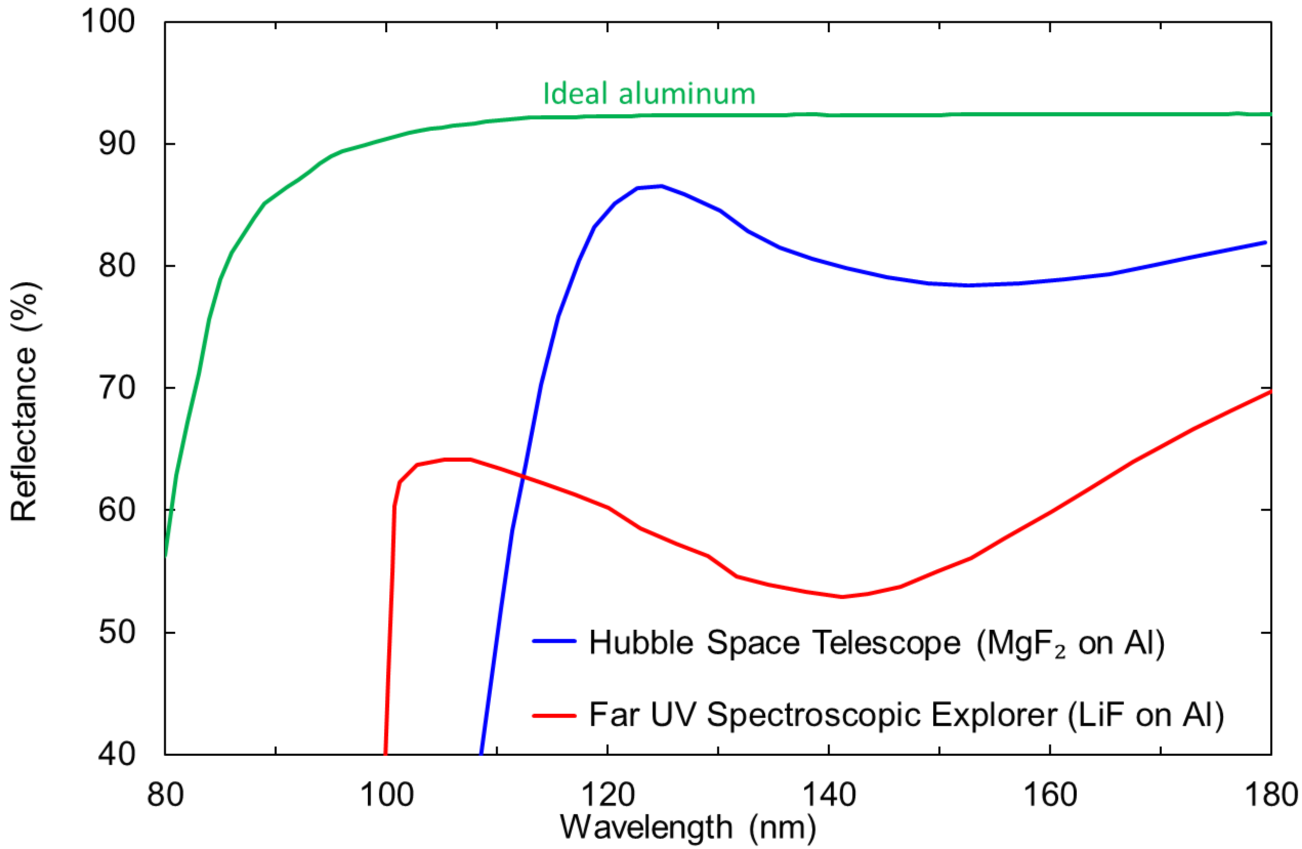
- Reduction of aluminum reflectance following air exposure has power law dependence on time
  - Power law exponent also has at least exponential dependence on wavelength

Protective layers

Properties of Typical Deposited Thin Films for UV Optical Applications		
Material	**Band Energy (eV)**	**~λ Cut Off (nm)**
lithium fluoride (LiF)	12 – 13	95
aluminum fluoride (AlF_3)	11 – 12	105
magnesium fluoride (MgF_2)	10 – 11	115
calcium fluoride (CaF_2)	9 – 10	125
lanthanum fluoride (LaF_3)	8 – 9	140
silicon oxide (SiO_2)	7 – 8	160
aluminum oxide (Al_2O_3)	6 – 7	190

- Aluminum has the highest reflectance in the ultraviolet, but reflectance below 200 nm is strongly suppressed by the presence of any surface oxide
- Protective coatings can be applied to pristine Al surfaces to prevent oxidation and even enhance reflectivity due to interference effects
- Currently developing and optimizing ALD processes at JPL for the three best candidate protective materials

Background

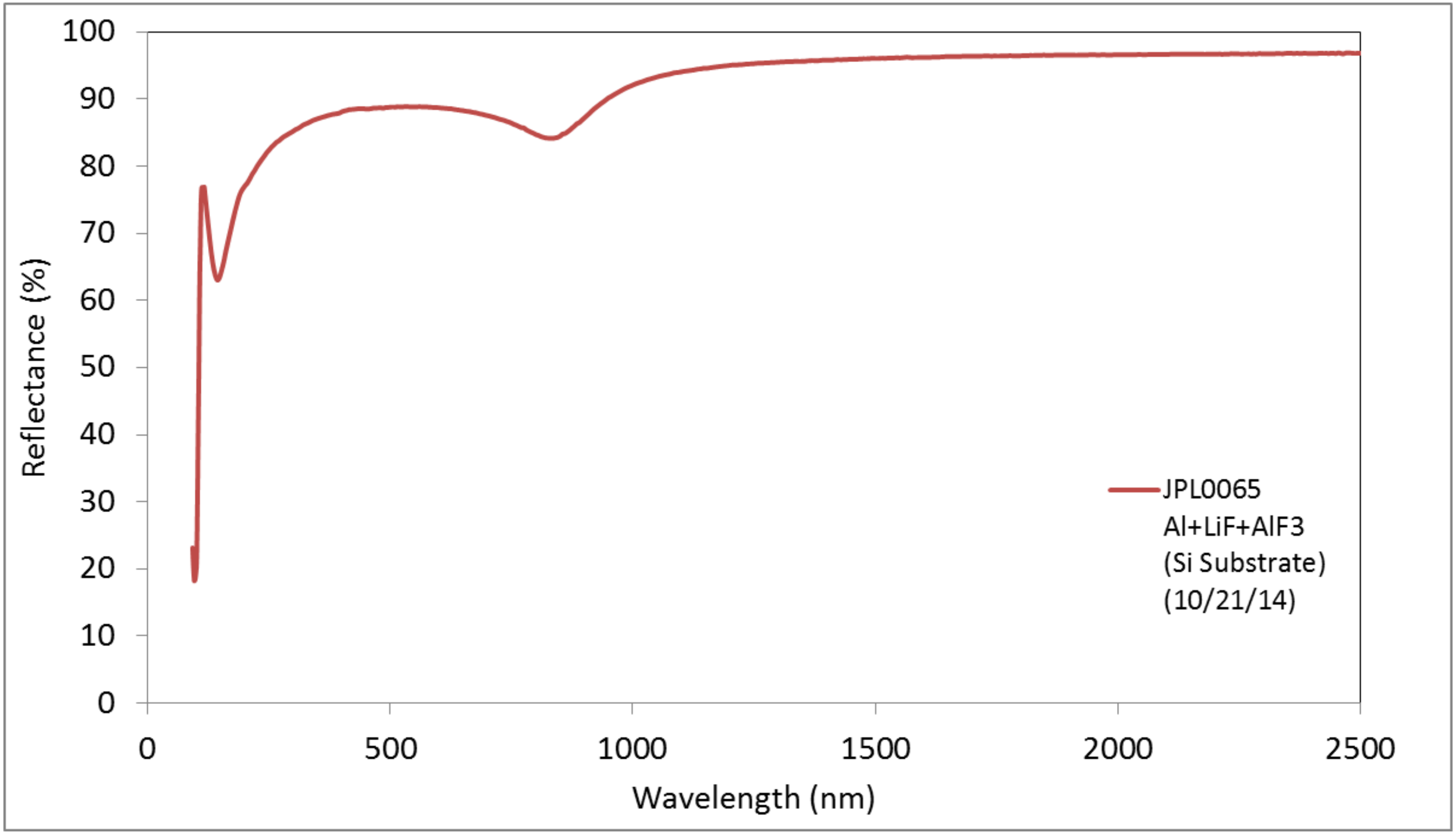


Ref:
Keski-Kuha et al., ASP Conference Series, vol. 164, (1999)

- Standard coatings fall well below the natural reflectance of aluminum
  - A **thin, dense, absorption free** protective coating could greatly improve performance from 90-120 nm
- FUV has a significant number of spectral lines that are of great interest to astronomers
  - Stellar and galaxy evolution; protoplanetary disks and exoplanet atmospheres

A Protected Aluminum Mirror

Conventional Deposition



Al+LiF+AlF_3 mirror aging performance

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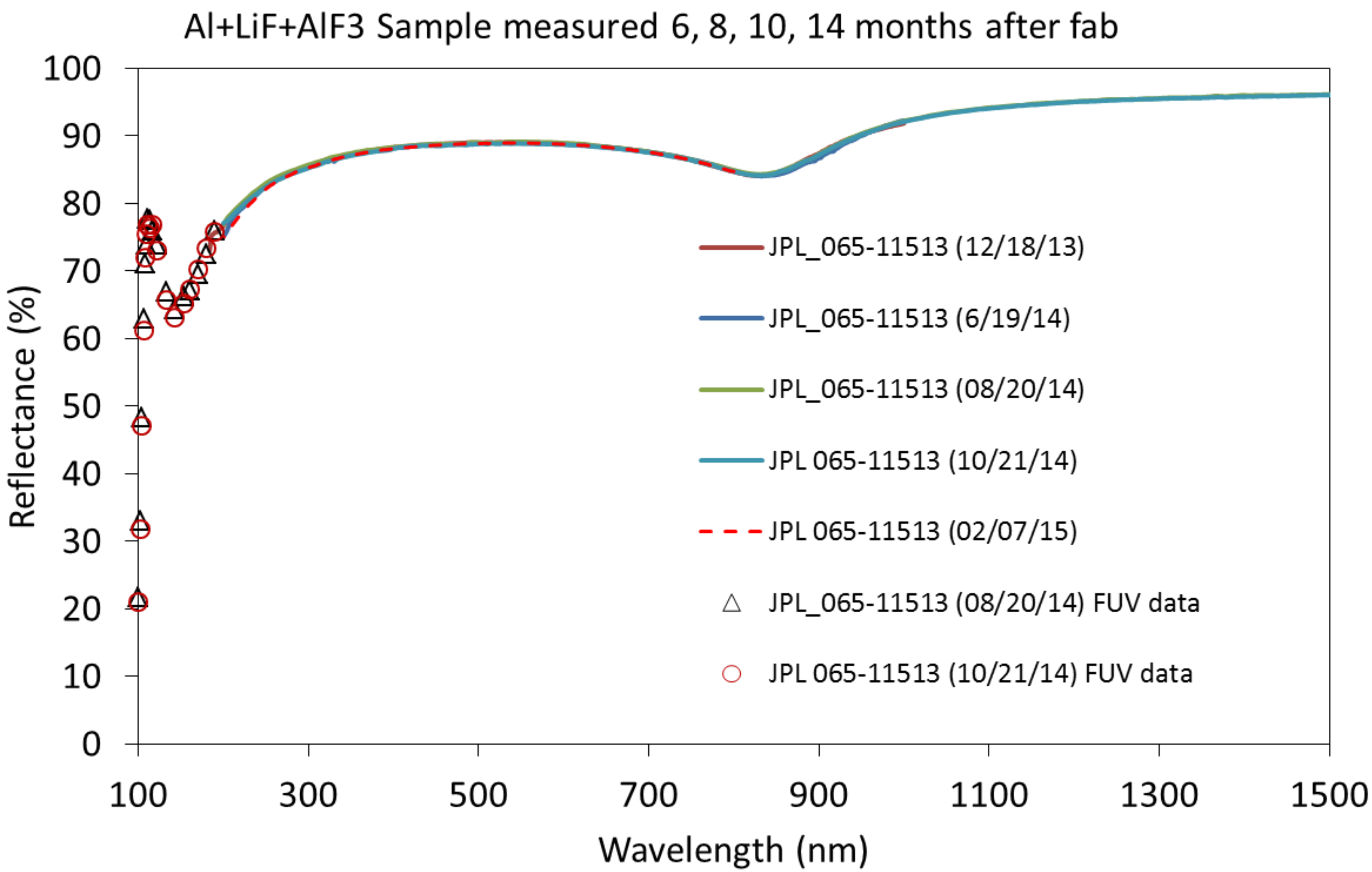
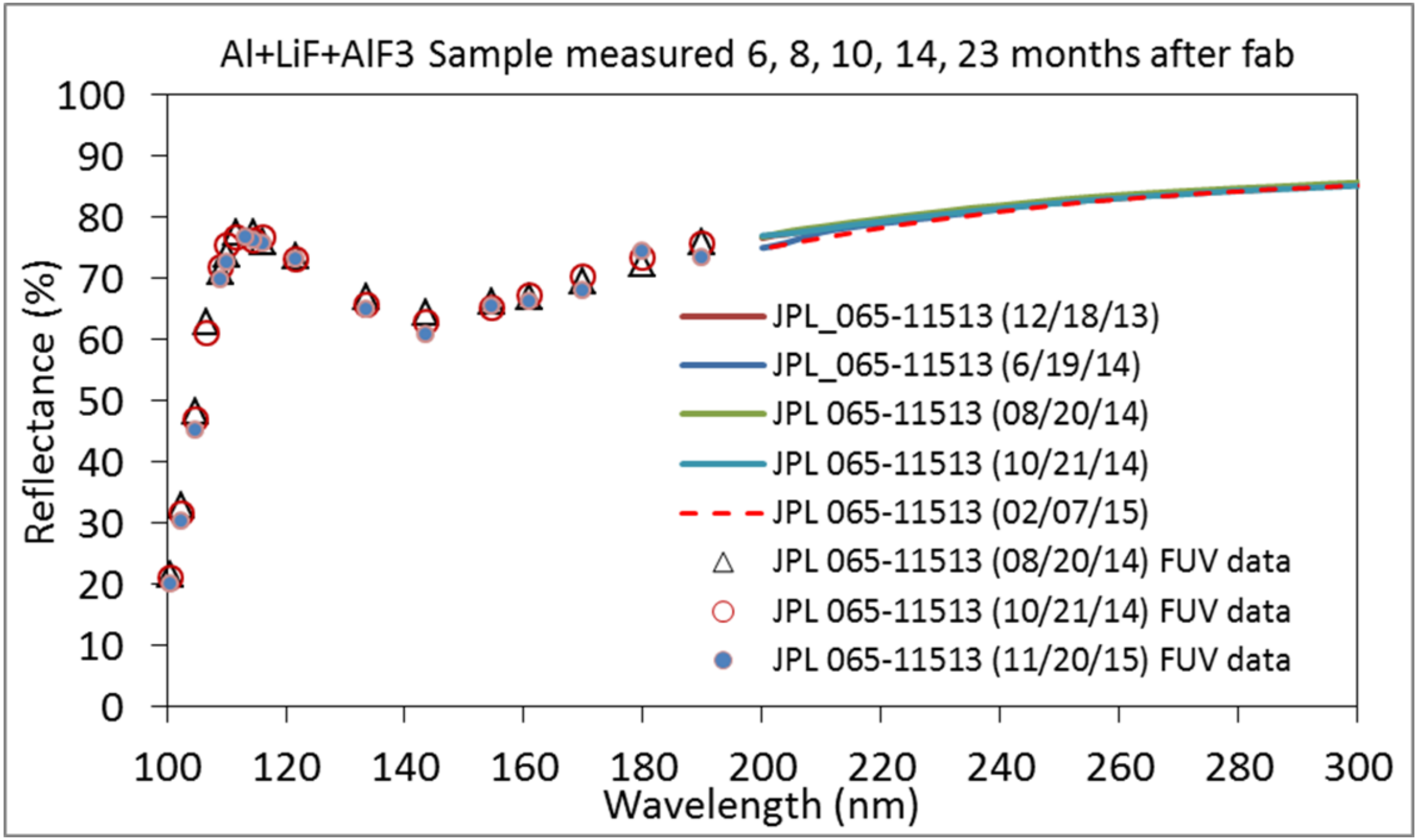
Conventional Thermal Evaporation



Measured reflectance of a bi-layer protected Al mirror sample measured 6, 8, 10 and 14 months after fabrication showing excellent stability. FUV to NIR spectral range.

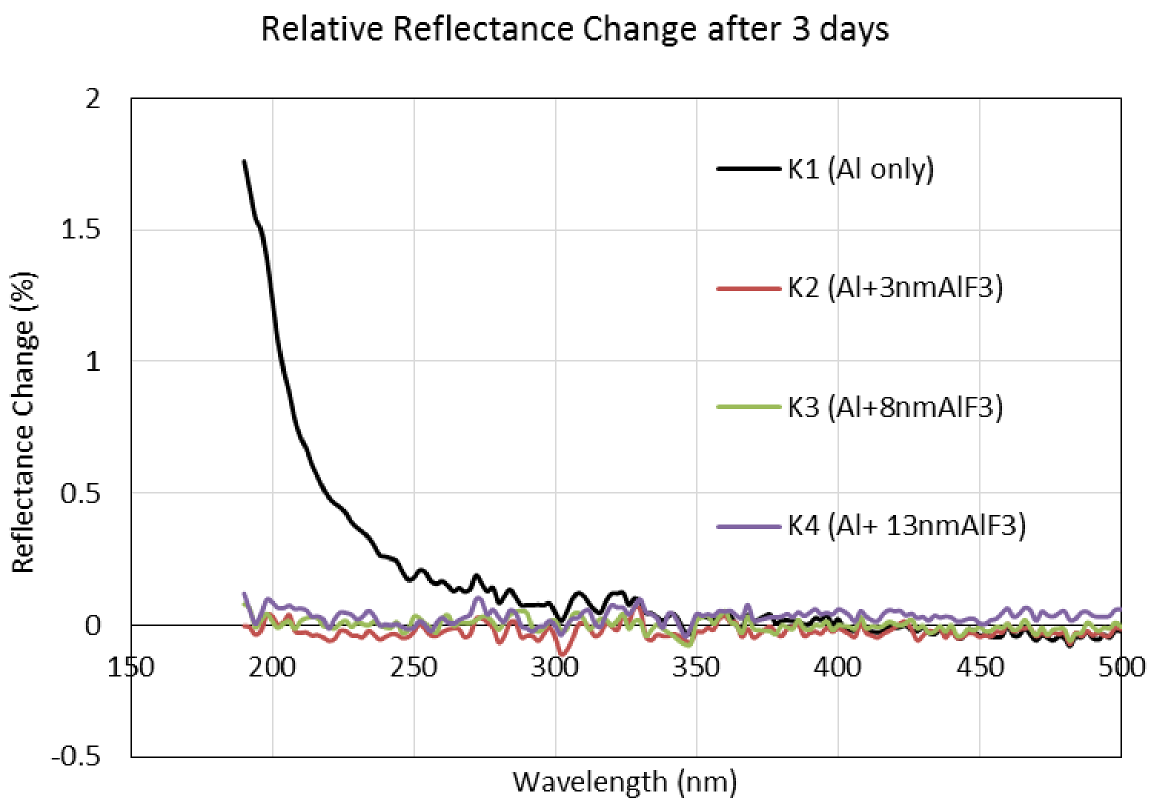
$Al+LiF+AlF_3$ mirror aging performance

Conventional Thermal Evaporation



Measured reflectance of a tri-layer Al mirror sample measured 6, 8, 10, 14 and 23 months after fabrication showing excellent stability. Expanded view of the FUV spectral range.

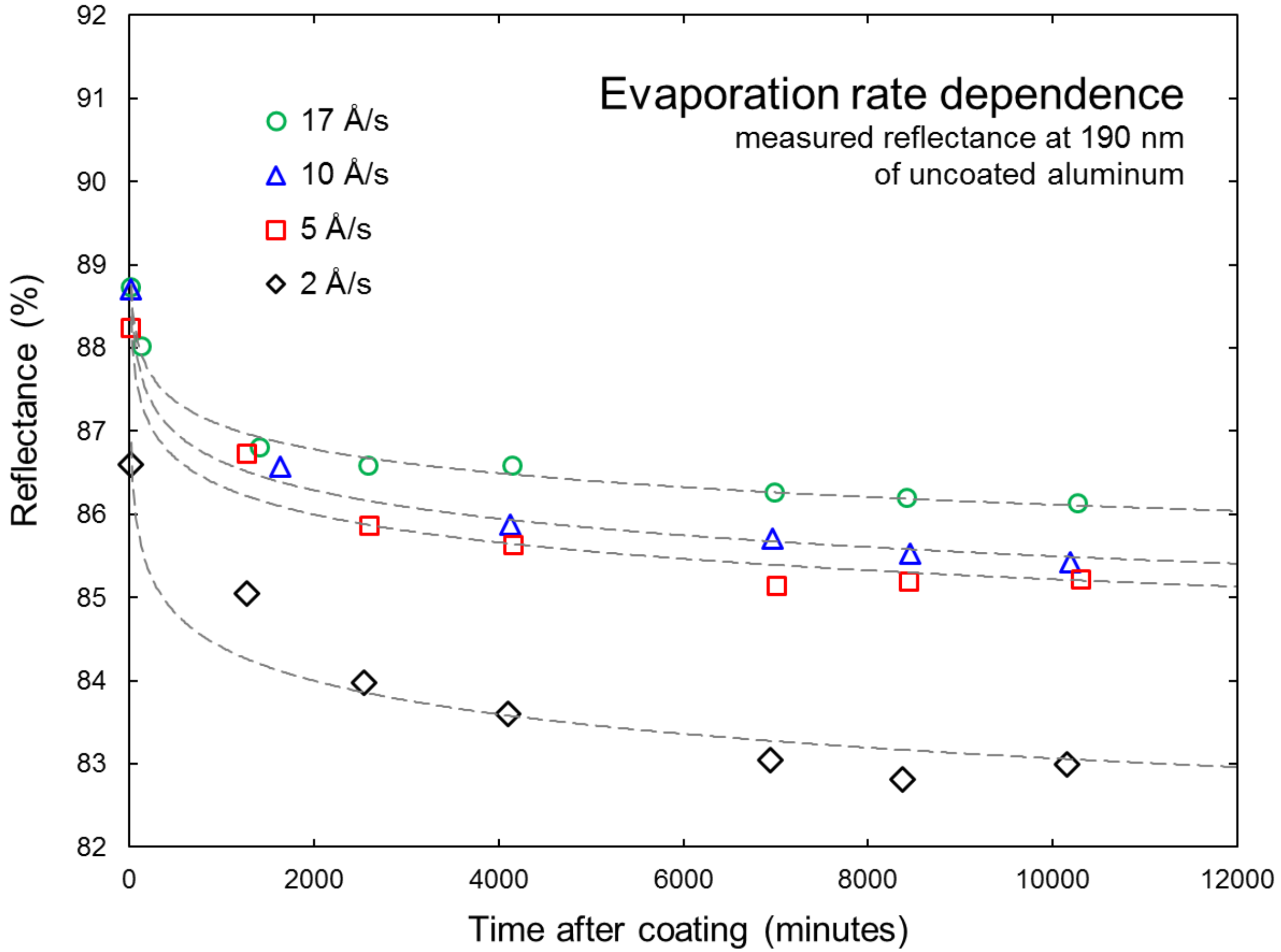
Stability of Al with Thin AlF_3 Layers by ALD



Stability of Al mirror (sample K series) coated with thin AlF_3 layer by ALD

- ALD AlF_3 coatings have a measured long-term stability, and can also extend the short wavelength cutoff when compared to traditional methods
- Layers as thin as 3 nm have been demonstrated to be effective in suppressing the oxidation of aluminum

Aluminum Evaporation Rate Dependence



- Even in UHV conditions (base pressure ~ 2 x 10^{-9} Torr), the reflectivity dependence on evaporation rate is significant
  - Impact on the saturated value of reflectance as well as the rate of degradation

FUV performance of ALD AlF_3/Al mirror samples

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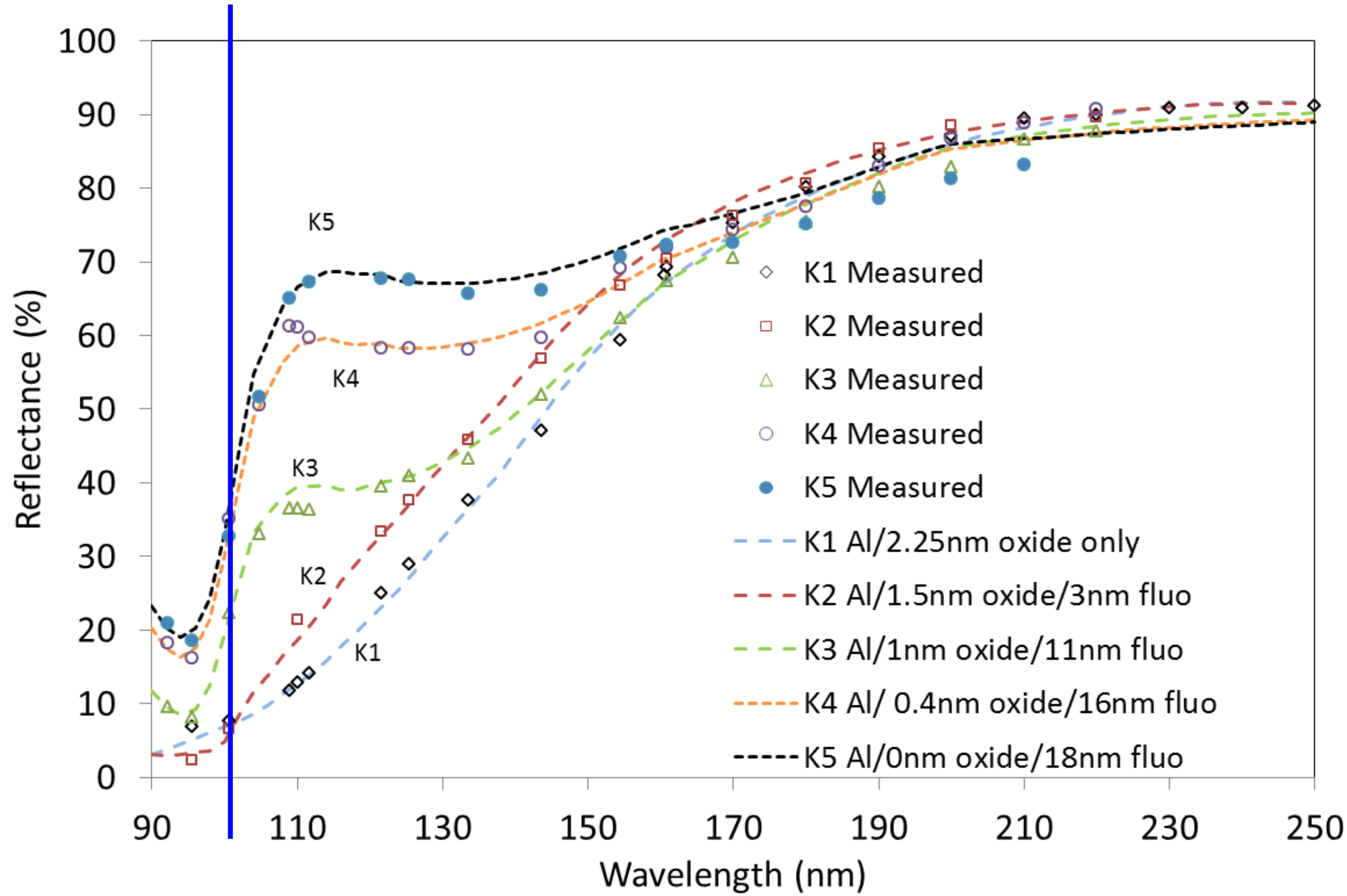
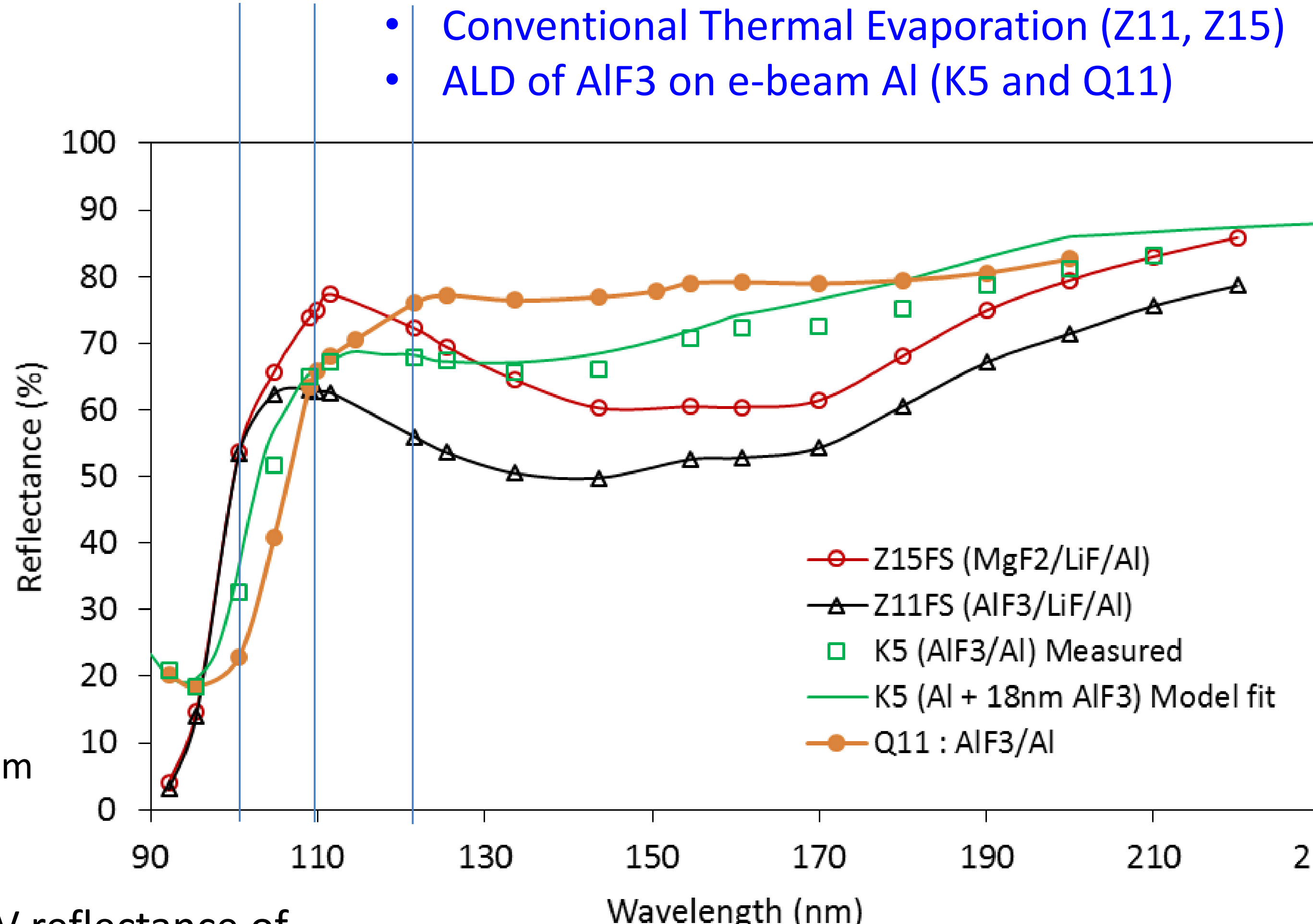


Model fits (dotted lines) of measured (symbols) FUV reflectance of unprotected (sample K1) and AlF_3 protected samples (K2 to K5).

Al+LiF+AlF_3 mirror, Al+AlF3(ALD) mirror

- Conventional Thermal Evaporation (Z11, Z15)
- ALD of AlF3 on e-beam Al (K5 and Q11)



Ly-a 121.6nm
Ly-b 102.6nm
Ly Limit 91.2nm
Balmer-g 108.5nm

- FUV reflectance of
  - tri-layer mirror samples produced by conventional thermal evaporation
  - bi-layer mirror samples produced by e-beam and ALD
- Optimization of layer thicknesses necessary to improve performance

Protected Al mirrors from JPL and GSFC

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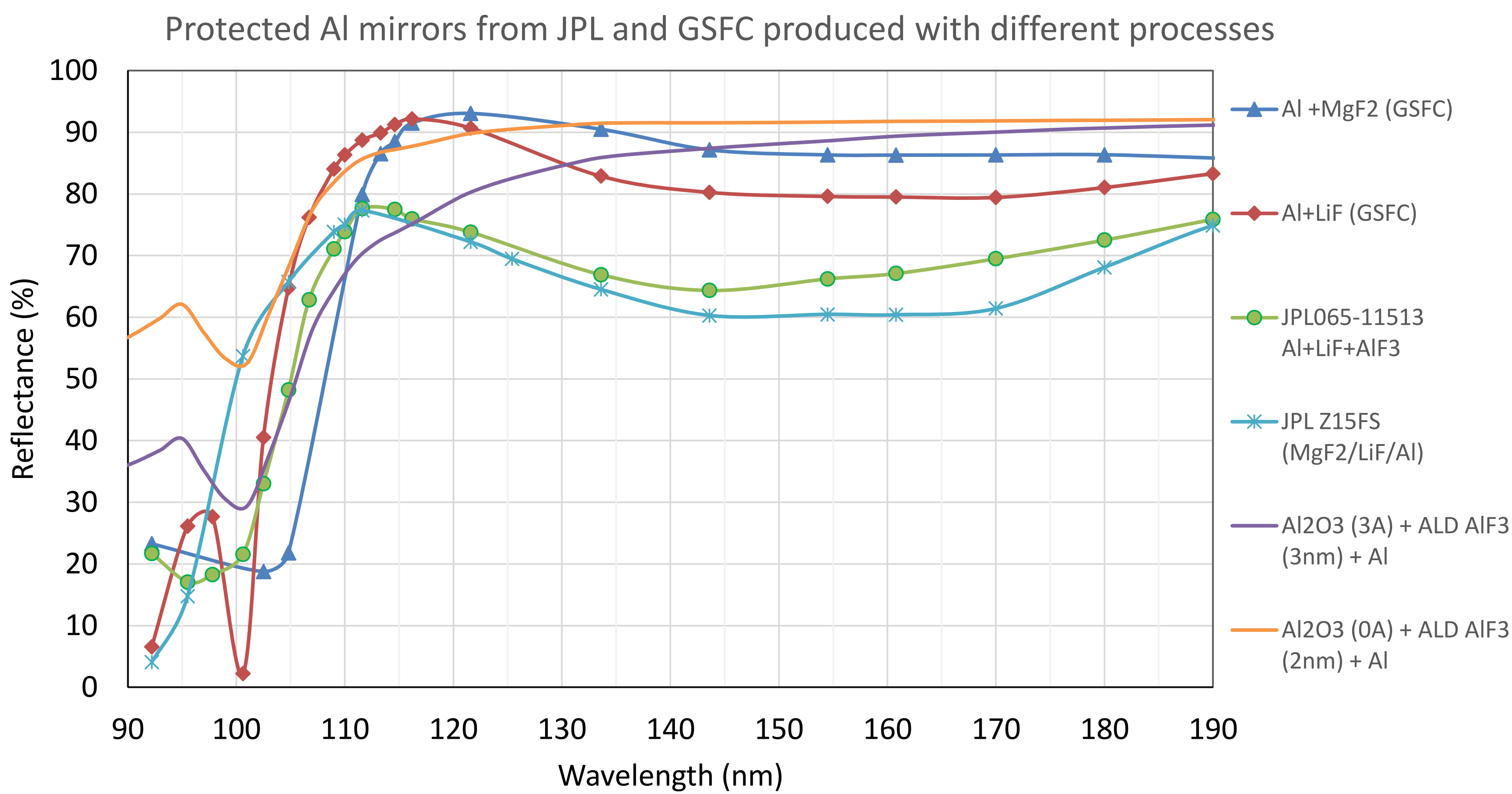
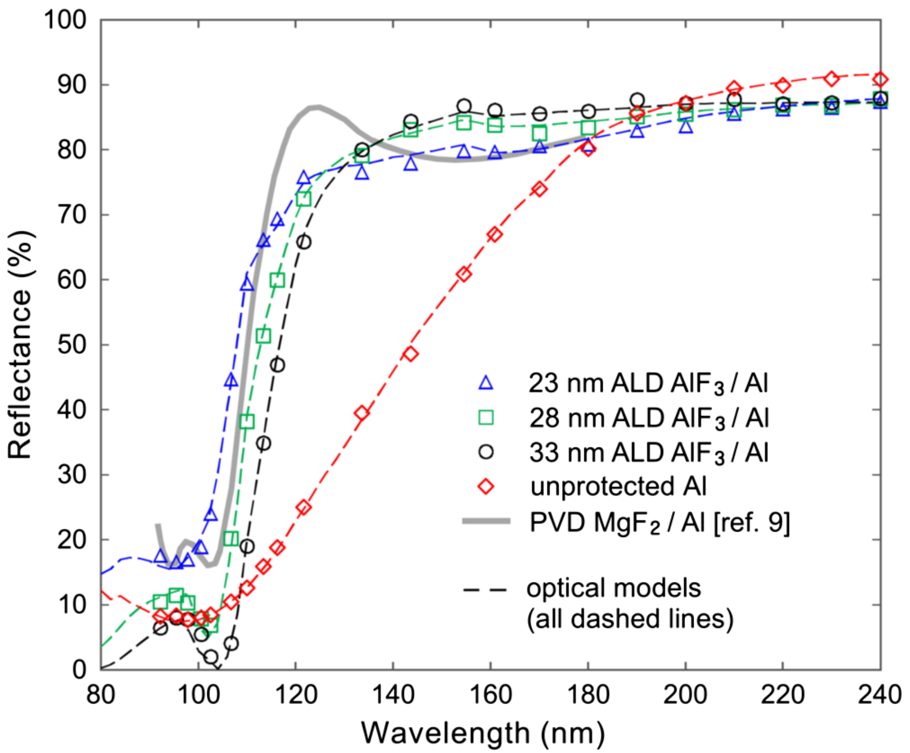
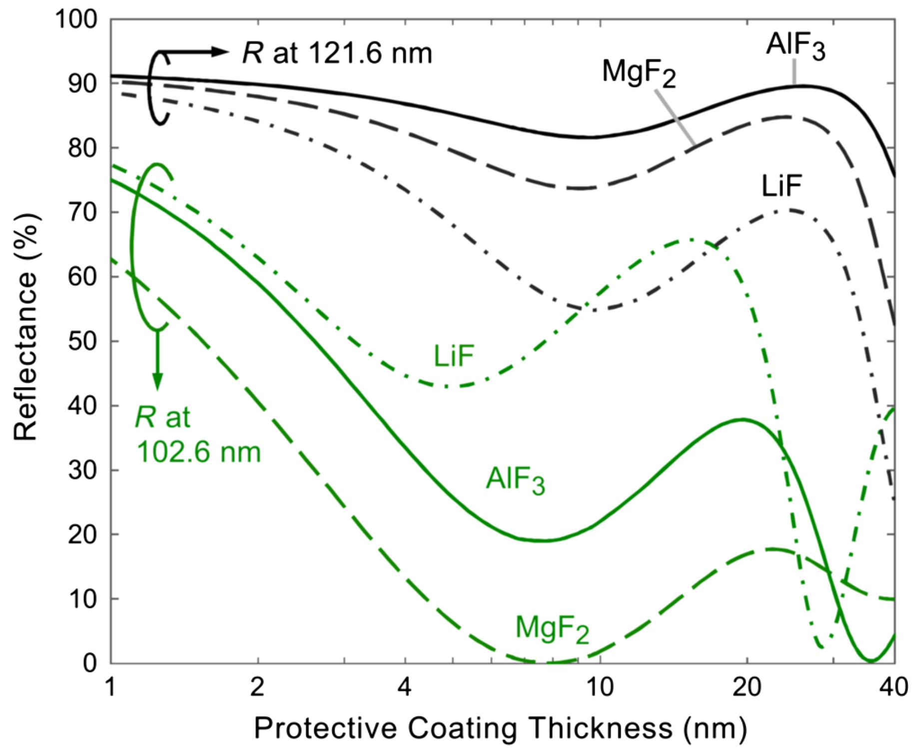


GSFC Data Courtesy: Manuel Quijada

Optimization





Measured FUV reflectance (symbols) and the corresponding calculated optical model (dashed lines) of ALD AlF3 protective coatings of various thickness deposited on evaporated Al thin films.

The calculated reflectance at 121.6 and 102.6 nm as a function of coating thickness for films of MgF_2, AlF_3, and LiF on ideal Al.

Throughput after 3 reflections: with 60% R from each optic at 100nm, throughput will be 0.6^3 = 0.22

J. Hennessy, et al., JATIS 2(4), 041206 (2016)

Summary

- Protected Aluminum mirrors with ~75% reflectance at 110nm with long term stability have been produced
- These mirrors currently show ~55% reflectance at 100nm
- Protective fluoride layers coated with Atomic Layer Deposition indicate potentially better performance (>60% at 100nm) and stability

- **References**

- Balasubramanian, *et al.*, Proceedings of SPIE vol. 9602-19 (2015)
- Hennessy, J., April D. Jewell, Frank Greer, Michael C. Lee, and Shouleh Nikzad. "Atomic layer deposition of magnesium fluoride via bis (ethylcyclopentadienyl) magnesium and anhydrous hydrogen fluoride." Jl. of Vacuum Science & Technology A 33, no. 1 (2015): 01A125.
- Hennessy, J., A. D. Jewell, K. Balasubramanian, and S. Nikzad, "Ultraviolet optical properties of aluminum fluoride thin films deposited by atomic layer deposition," (submitted) Jl.of Vacuum Science & Technology A, JVST A 34, 01A120 (2016).
- J. Hennessy, Kunjithapatham Balasubramanian, Christopher S. Moore, April D. Jewell, Shouleh Nikzad, Kevin France, Manuel Quijada, "*Performance and prospects of far ultraviolet aluminum mirrors protected by atomic layer deposition*," J. Astron. Telesc. Instrum. Syst. 2(4), 041206 (2016), doi: 10.1117/1. JATIS.2.4.041206

Acknowledgements

John Hennessy, Shouleh Nikzad, Nasrat Raouf, Stuart Shaklan, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Paul Scowen, Arizona State University, Tempe, AZ 85287

Manuel Quijada, Javier Del Hoyo, NASA – GSFC (FUV Reflectance)

David Sheikh, and Josh Saadia, Zecoat Corporation, Torrance, CA

The work is performed at Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA Cosmic Origins Program

Thank You

Backups

Significant FUV Spectral Lines

Courtesy: Paul Scowen

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Wavelength (nm)	Species	Significance
68.1, 69.4	Na IX	Coronal Gas (> 10^6 K) Diagnostic (density, ionization state, etc.)
77.0	Ne VIII	Warm-Hot Gas (5×10^5 - 10^6 K) Diagnostic (density, ionization state, etc.)
91.2	H, Lyman Limit	Ionization Energy of Atomic Hydrogen
97.7	C III	Gas Electron Density Diagnostic
99.1, 175.0	N III	Gas Temperature Diagnostic
102.6	H, Ly-β	Lyman Series H Recombination Line
103.2, 103.8	O VI	Recombination Line Doublet
108.5, 164.0	He II	Balmer-γ line for He
117.5	C III	Gas Electron Density Diagnostic
120.6	Si III	Optically thin emission line of Silicon
121.6	H, Ly-α	Lyman Series H Recombination Line
123.8, 124.3	N V	Gas Emission Diagnostic
130.4	O I	Geocoronal Triplet Emission Line
133.5	C II	Absorption Line for ionized Carbon
139.4, 140.3	Si IV	Emission Line of Silicon
140.7	O IV]	Gas Density sensitive doublet
148.8	N IV]	Gas Diagnostic Line – sensitive in particular to electron collision strengths
154.8, 155.1	C IV	Gas density-sensitive doublet

Kepler

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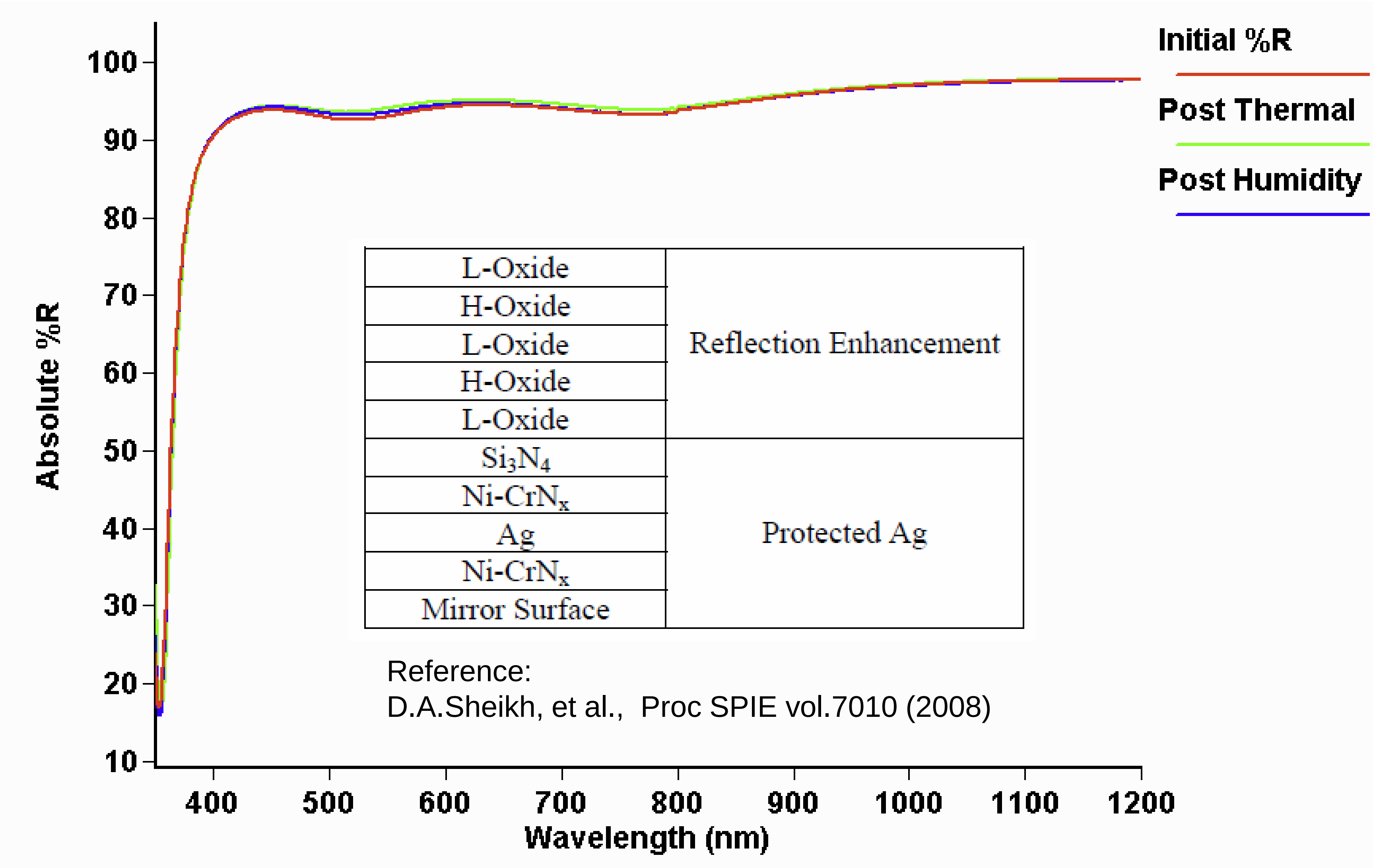

L-Oxide	Reflection Enhancement
H-Oxide	
L-Oxide	
H-Oxide	
L-Oxide	
Si_3N_4	Protected Ag
$Ni\text{-}CrN_x$	
Ag	
$Ni\text{-}CrN_x$	
Mirror Surface	

Reference:
D.A.Sheikh, et al., Proc SPIE vol.7010 (2008)

Kepler

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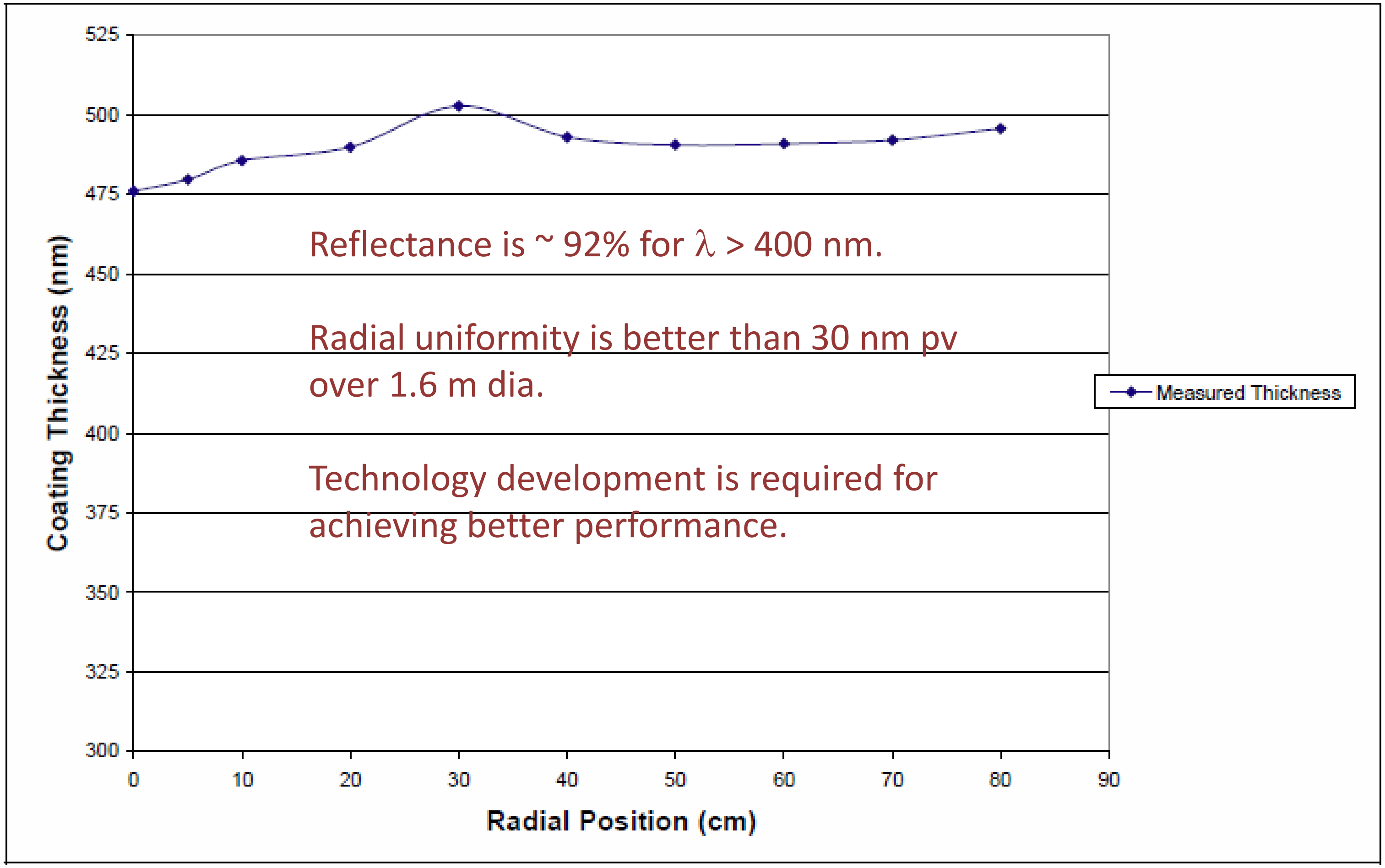


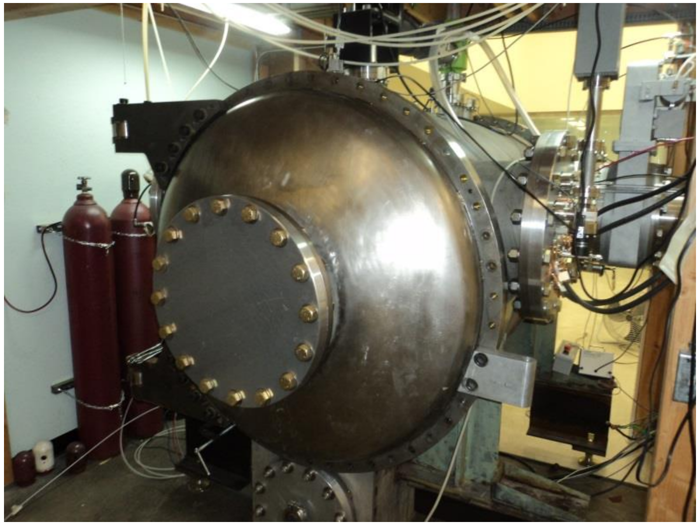
Reflectance is ~ 92% for λ > 400 nm.

Radial uniformity is better than 30 nm pv over 1.6 m dia.

Technology development is required for achieving better performance.

Reference:
D.A.Sheikh, et al., Proc SPIE vol.7010 (2008)

Deposition Chambers

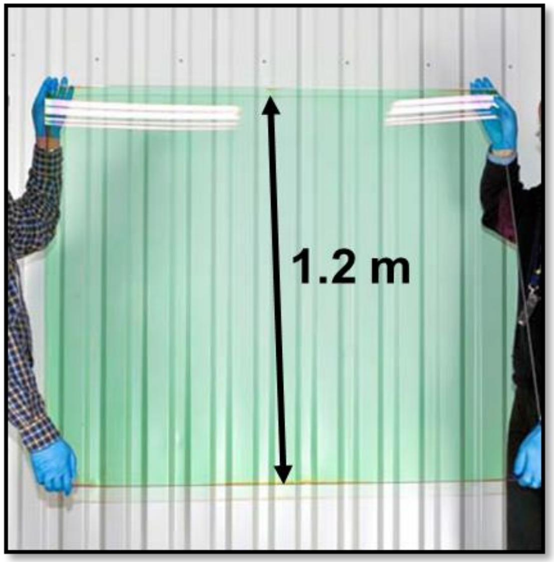


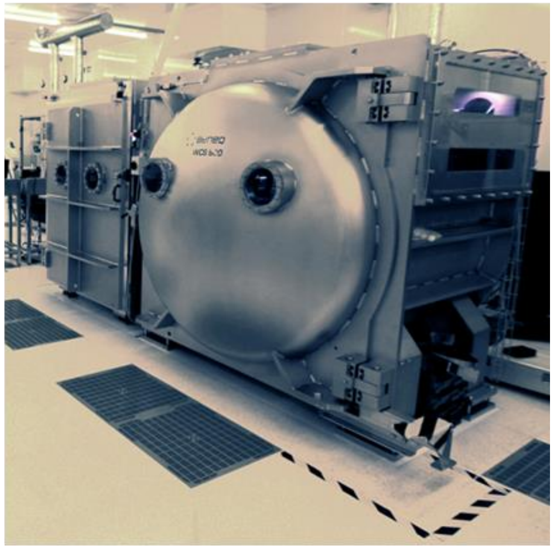
1.2m thermal / ebeam evaporation chamber (Zecoat Corp) with a moving source

Beneq ALD reactor (JPL)

Oxford ALD reactor (JPL)

Large ALD chambers





Commercial solutions for large area atomic layer deposition include (left) systems for high performance optical coatings [MLD Technologies, mldtech.com], (middle) deposition on meter-class substrates for photovoltaic applications [Putkonen 2009], and (right) large area roll-to-roll ALD reactor [Beneq, beneq.com]

VUV enhanced Al mirrors

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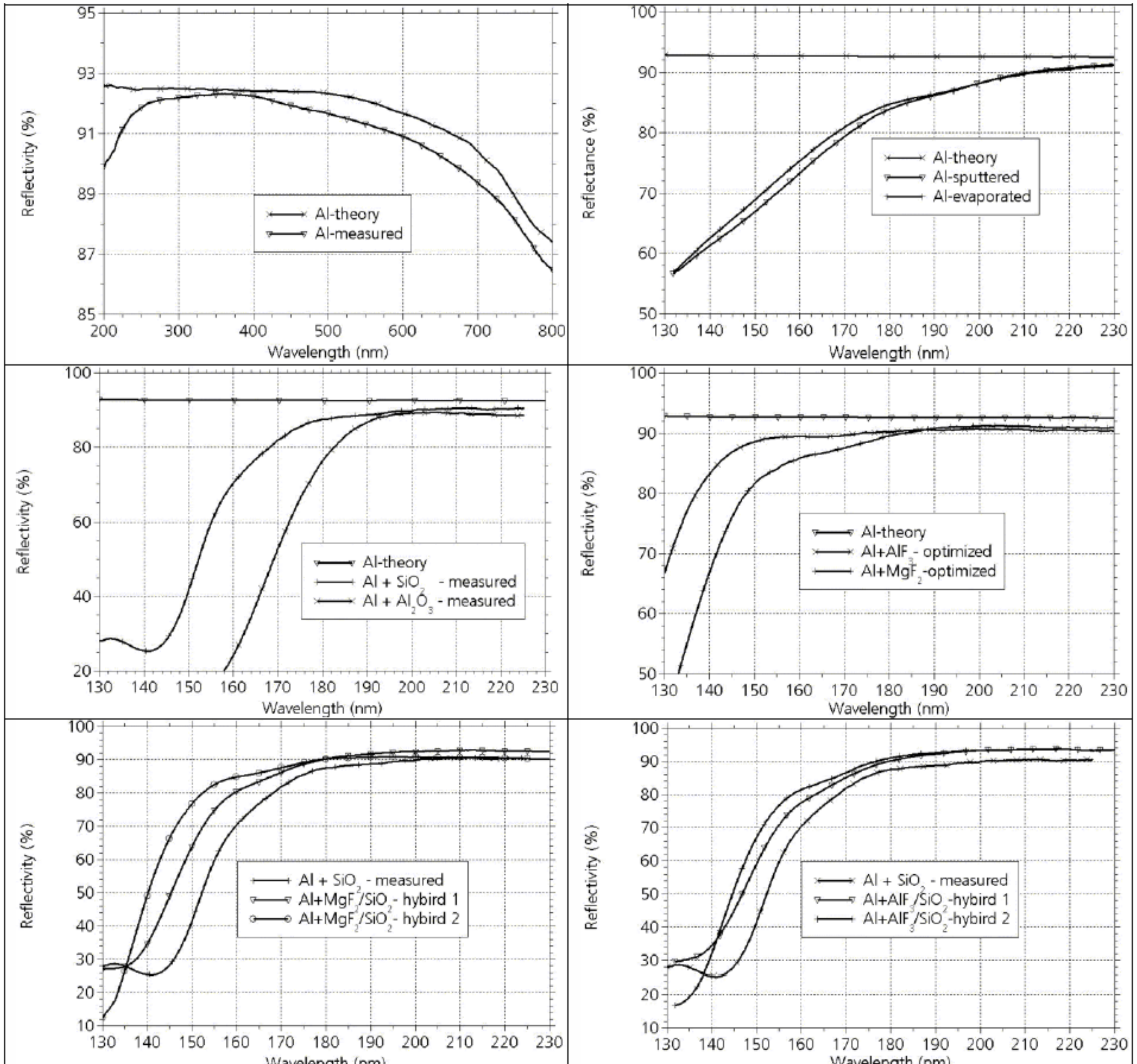
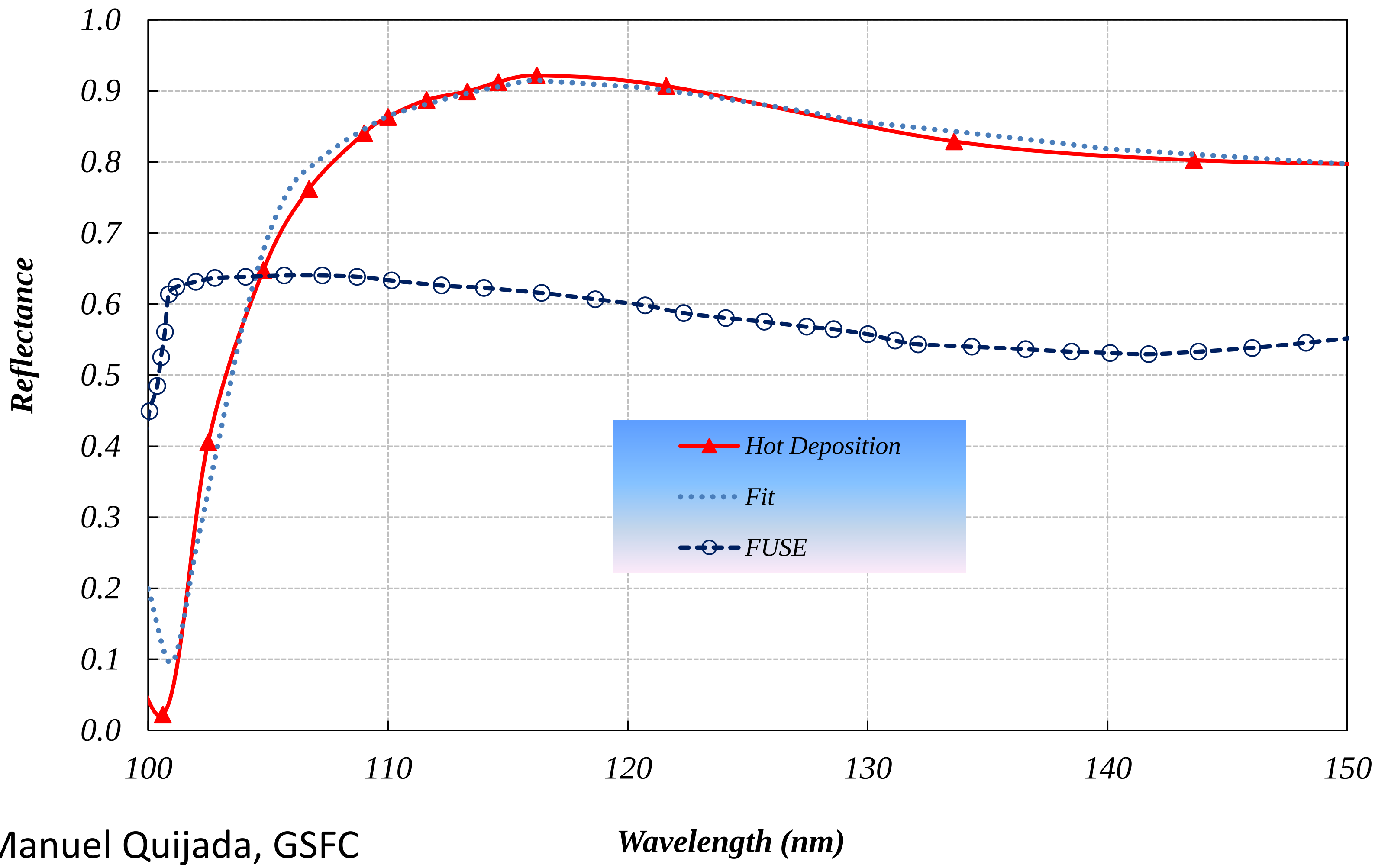


. Measured reflectivity of Al mirrors with various protective layers

Figures adopted from Yang, Gatto and Kaiser, Proc SPIE vol 5693, (2005)

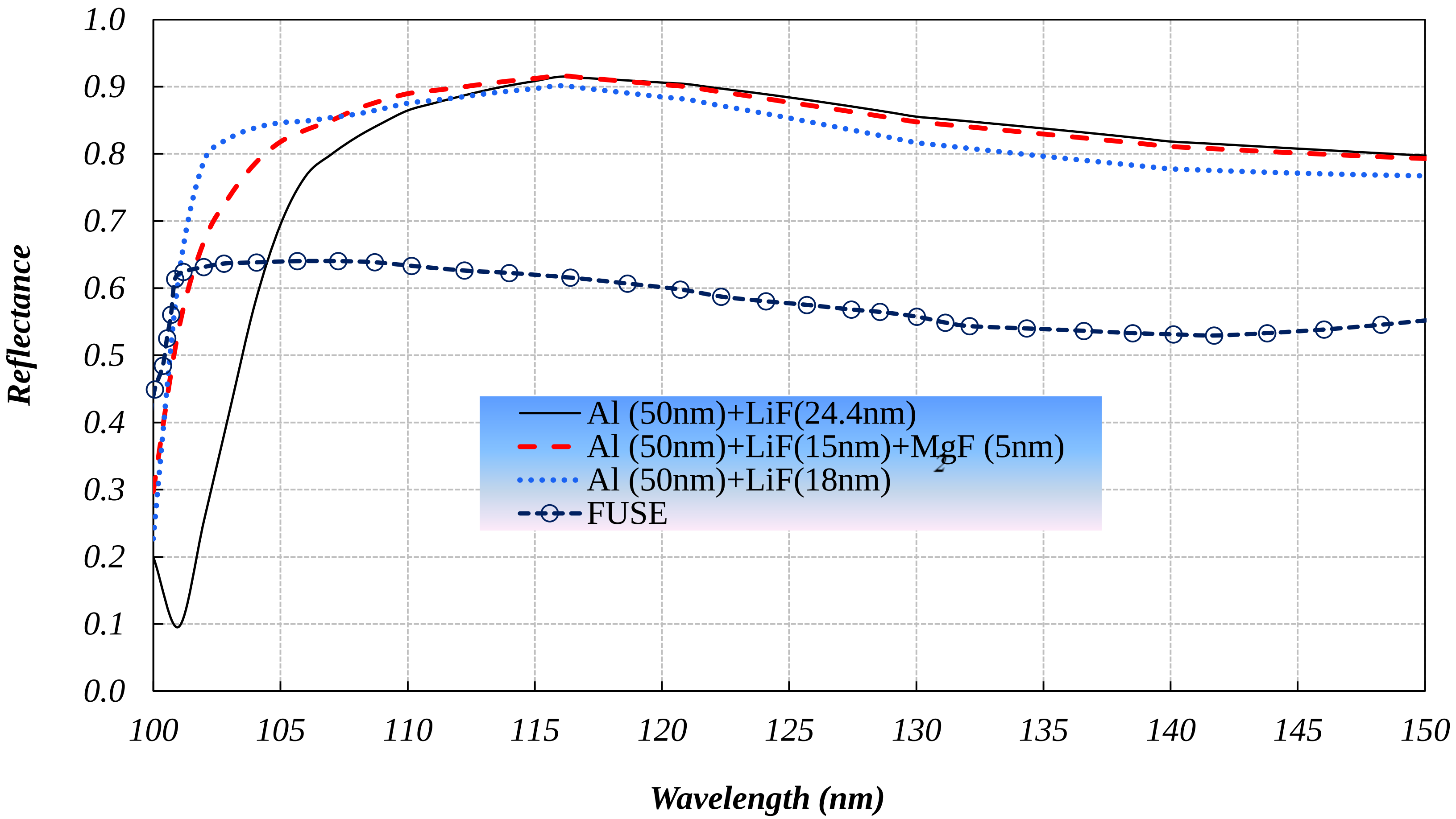
Al+LiF Mirror FUV Performance (GSFC)



Manuel Quijada, GSFC
Sep 2014

Recipe: Al (43nm, ambient)+LiF(8nm, ambient)+LiF(16.4nm, 250°C)
R_{ave}(100-150nm): 59% (FUSE) 75% (Hot)

Al+LiF Mirror FUV Performance Cont..



Manuel Quijada, GSFC
Sep 2014

Polarization

Oblique Incidence on Mirrors

- p and s Reflectances and Phase differences are different and vary with angle of incidence (AOI)
- Consequence ➔ phase and amplitude maps of orthogonal polarizations are quite different across the aperture
- Leakage terms from cross polarizations also have different amplitudes and phases
- DM can not correct wavefront error for both x and y polarizations simultaneously ➔ inadequate wavefront correction for coronagraphy
- Potential solutions ➔ optimized coatings through design and manufacture
- How well we can do this?
- If polarization effects can be mitigated, can we remove the polarizers thus simplifying design?

Different Approaches

1. Apply one optimum coating to all surfaces, preferably single layer for simplicity
2. Compensate polarization effect from one surface by different coatings on another surface
2. Apply tapered coatings over the aperture to mitigate angle of incidence effects
3. Add a correction optic, such as a diffractive element

Pupil Fields

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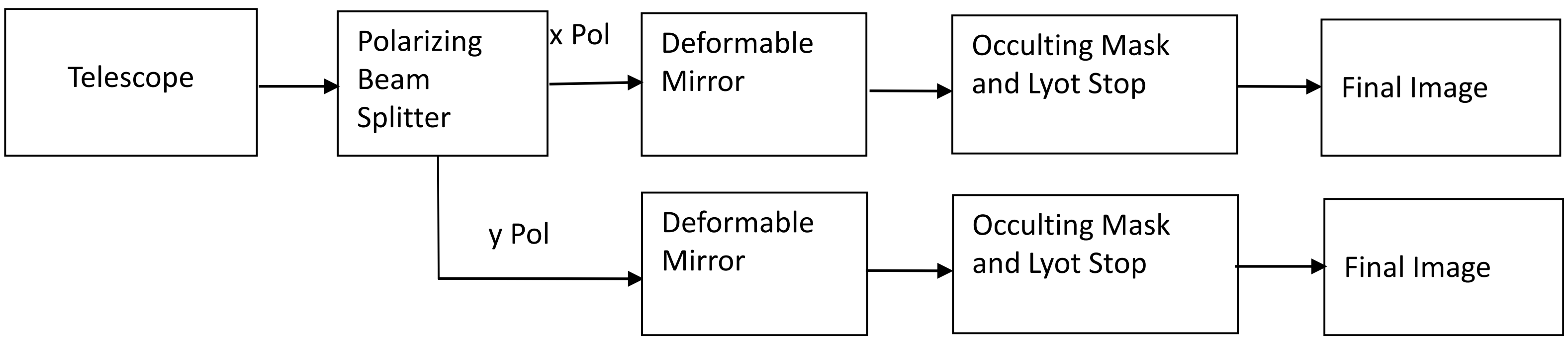
Total Field

Y polarization main term

Y polarization cross term

$$A_{xx}e^{i\phi_{xx}} + a_{xy}e^{i\phi_{xy}} + A_{yy}e^{i\phi_{yy}} + a_{yx}e^{i\phi_{yx}}$$



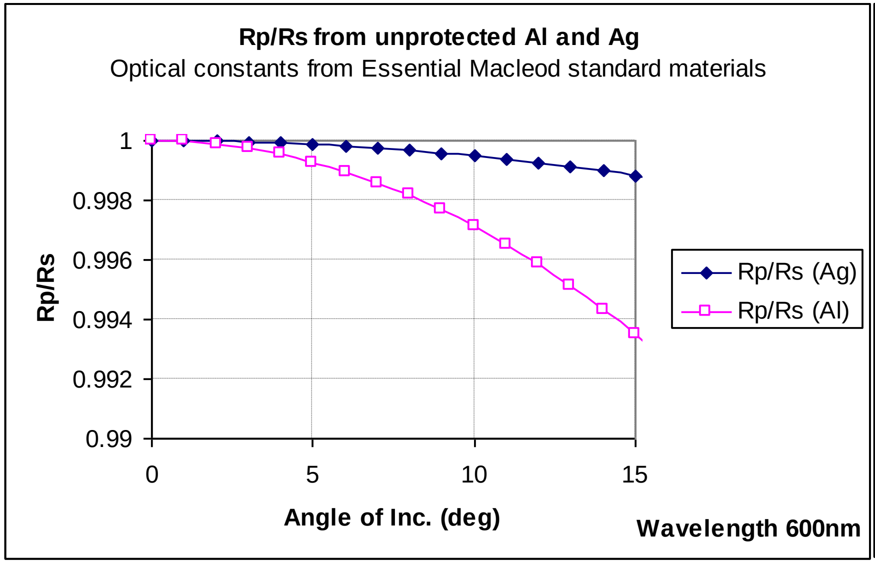
X polarization field after DM correction

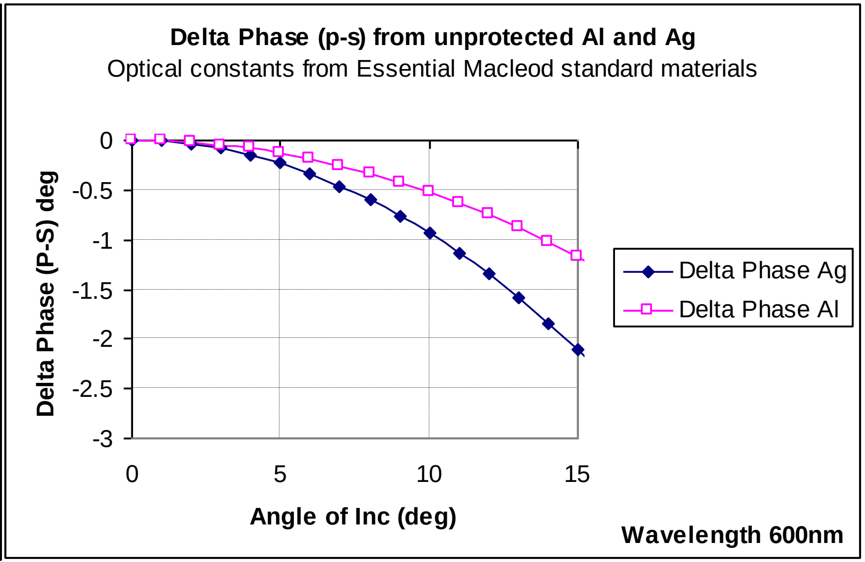
$$1+\left(\frac{a_{xy}}{A_{xx}}\right)e^{i(\phi_{xy}-\phi_{xx})}$$

Leakage or residual due to cross term

Balasubramanian, et al, Proc SPIE 5905, 2005

Polarization





Wavelength = 600nm

Unprotected Aluminum

For R ≈ 91%,

Six surfaces will yield a throughput of

$(0.91)^6 = 0.568$

Four surfaces will yield

$(0.91)^4 = 0.685$

For R = 86%

Four surfaces yield

$(0.86)^4 = 0.547$

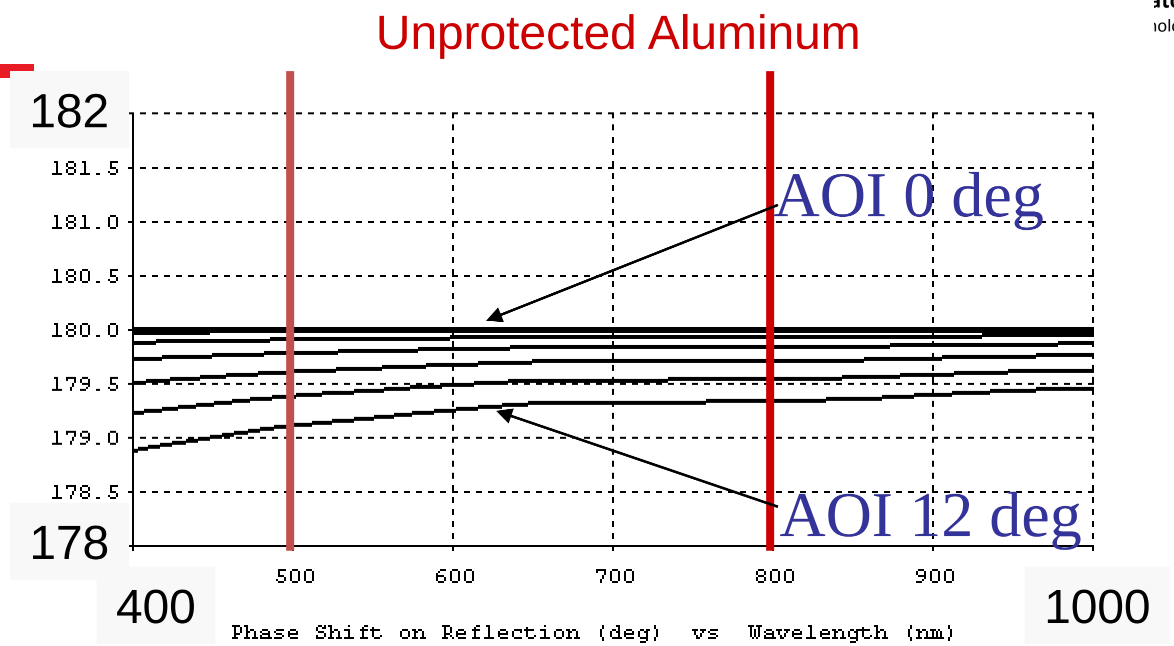
At AOI = 12 deg

Rp at 800nm = 86.2%

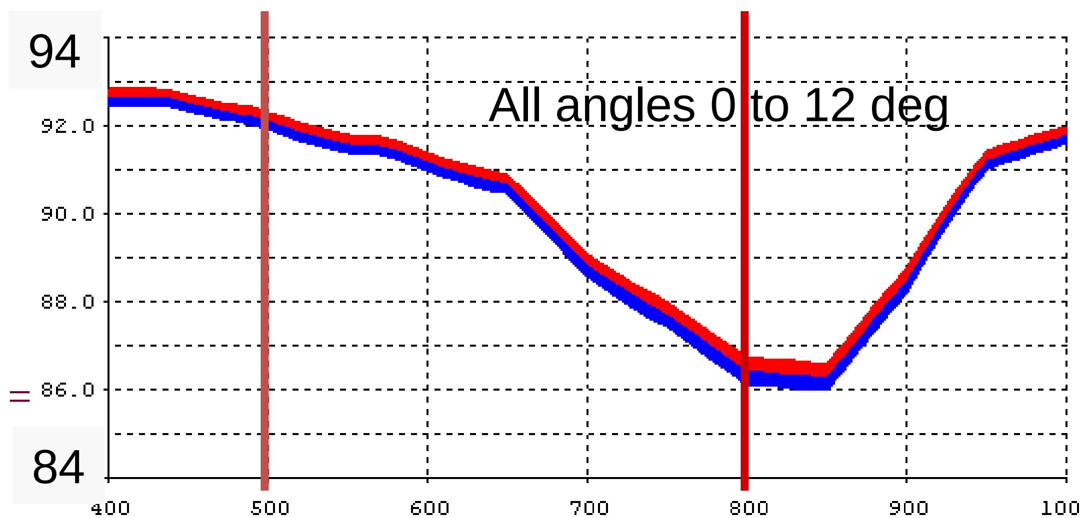
Rs at 800nm = 86.8%

ΔR at 800nm = 0.6%

ΔR at 800nm after 4 surfaces = 1.6%

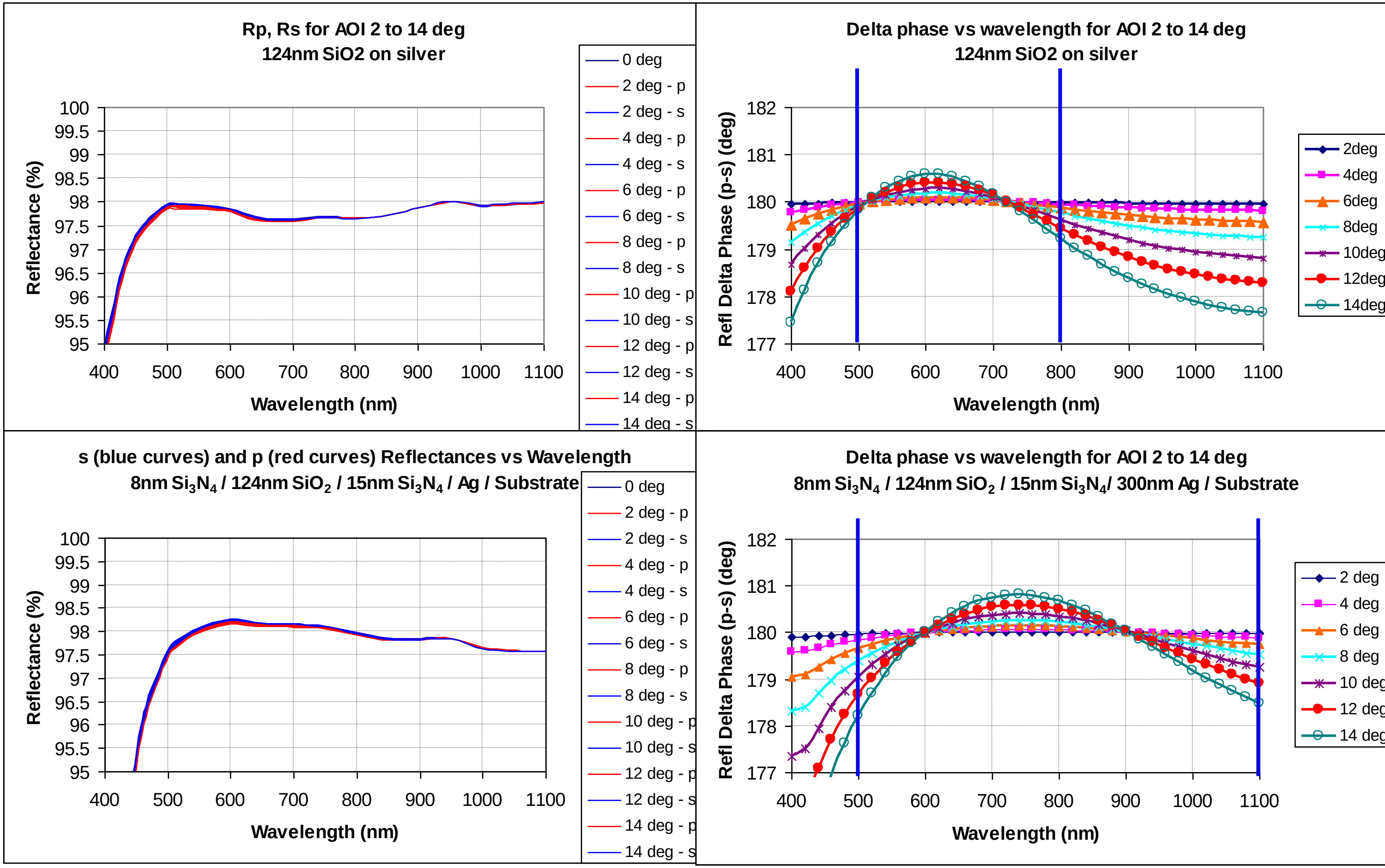


Phase difference (deg) bet p and s on reflection vs Wavelength (nm)

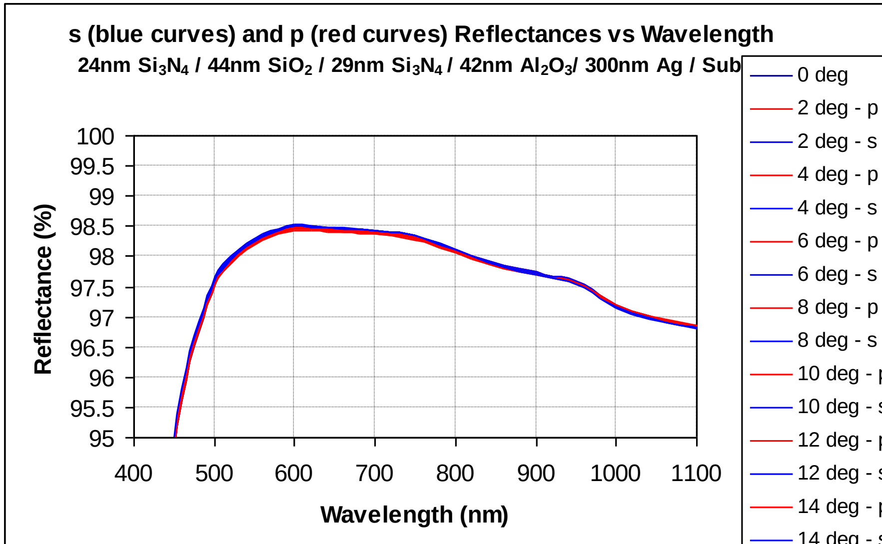


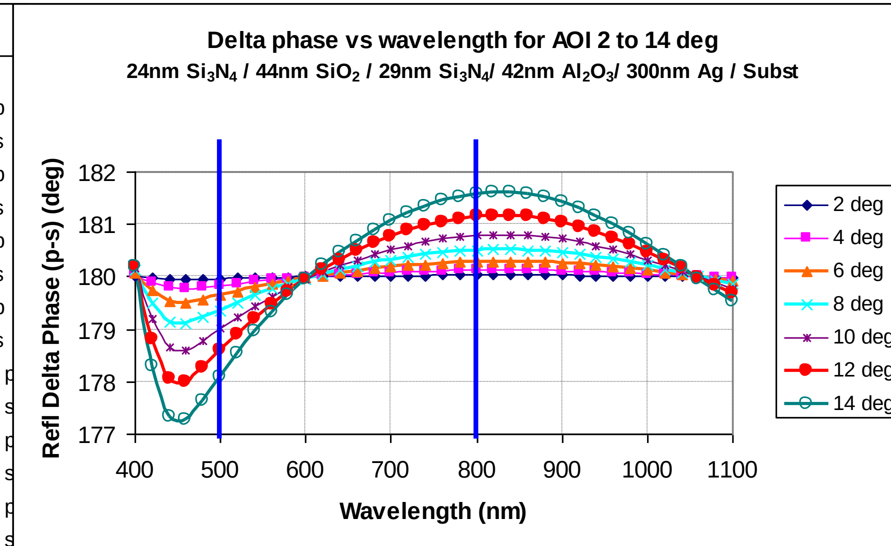
Reflectance (%) vs Wavelength (nm)

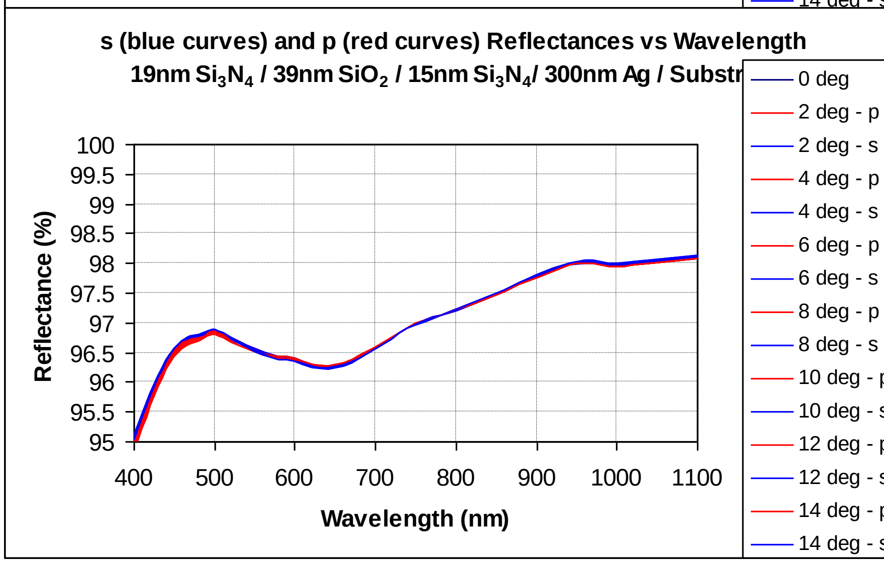
Single layer SiO_2 protection

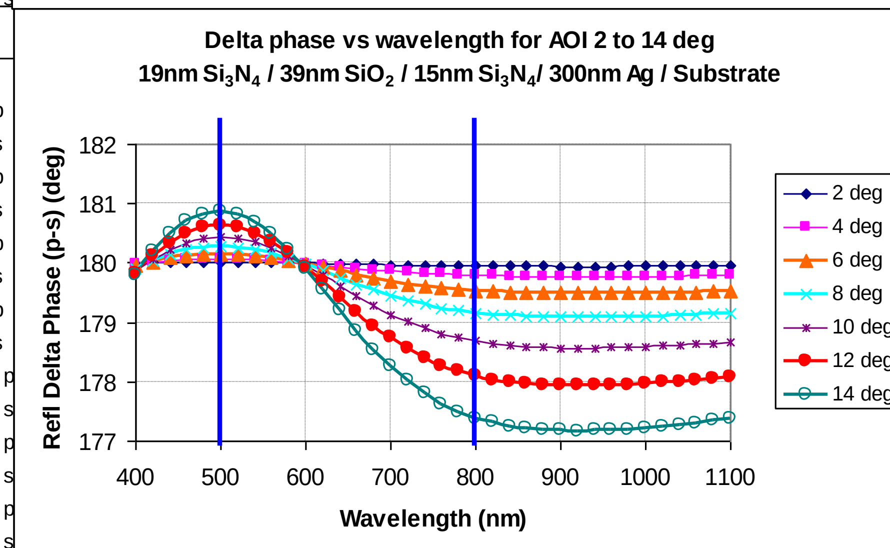


Complementary coatings









A Case Study for TPF coronagraph telescope architecture

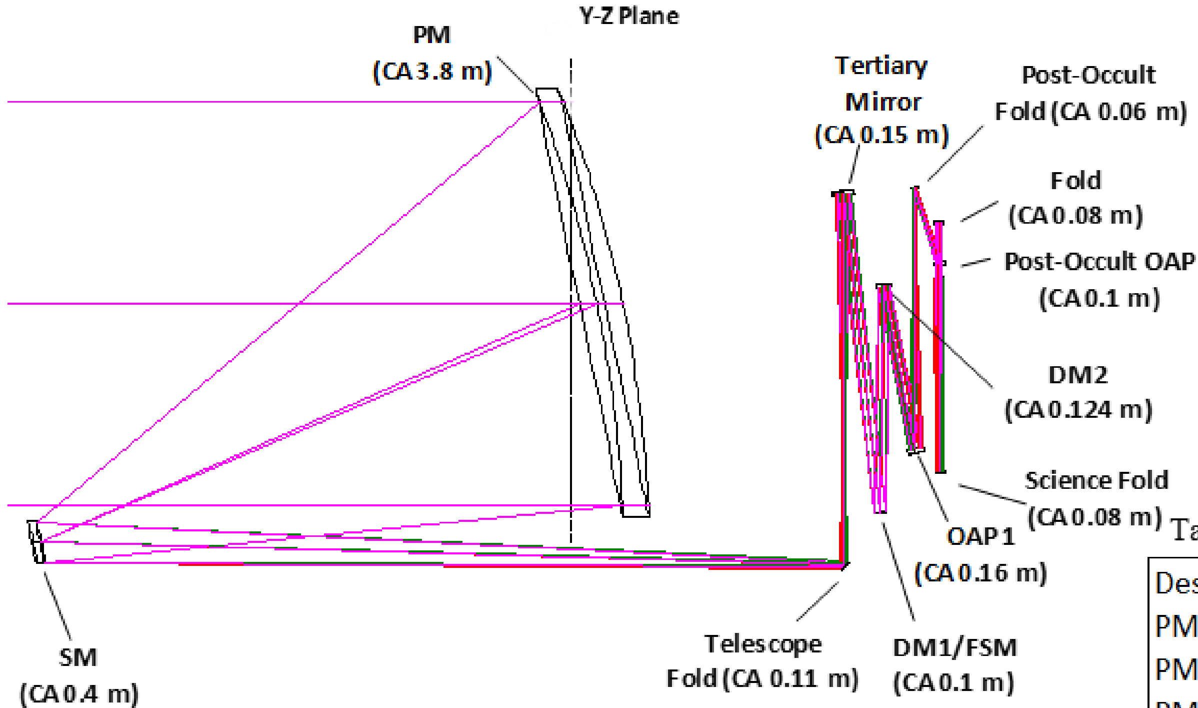


Figure 1. Telescope and instrument layout

Table 1. Telescope Design Parameters

Design	Cassegrain
PM Diam	4 m
PM Clear Ap.	3.8 m
PM-SM separation	5.5 m along Z axis
PM ROC, conic	12.155 m, k=-1
PM Parent f/no	F/0.69
PM Angle of Incidence	2.8-19.9 deg
Off-axis displacement	2.5 m
SM ROC, conic	1.237 m, k=-1.3057

Deep UV to NIR space telescopes and exoplanet coronagraphs:
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Kunjithapatham Balasubramanian, Stuart Shaklan, Amir Give'on, Eric Cady and Luis Marchen
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove drive, Pasadena, CA 91109
Techniques and Instrumentation for Detection of Exoplanets V, edited by Stuart Shaklan,
Proc. of SPIE Vol. 8151 (2011)

A Case Study cont'd……

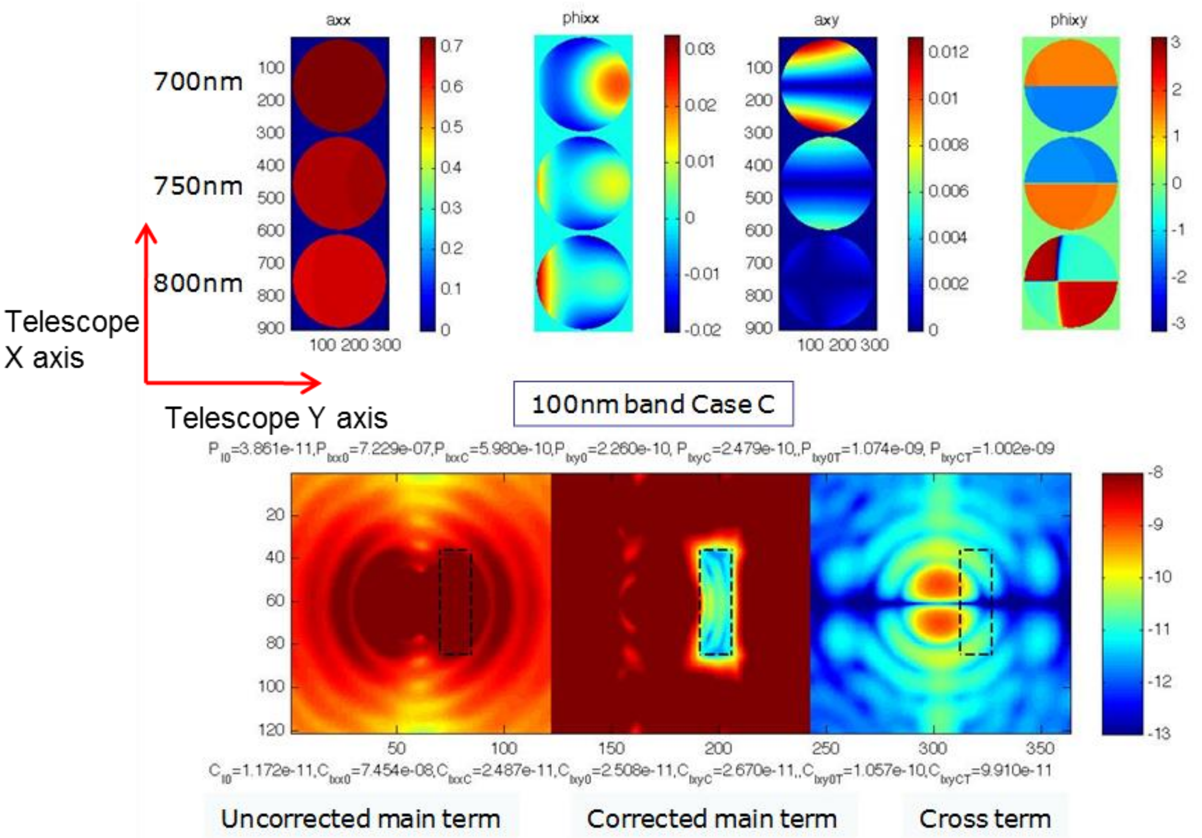

Figure 13. Case C. LiF/MgF_2 protected Al mirrors per tables 3 and 4 in the reference below

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A Case Study cont'd……

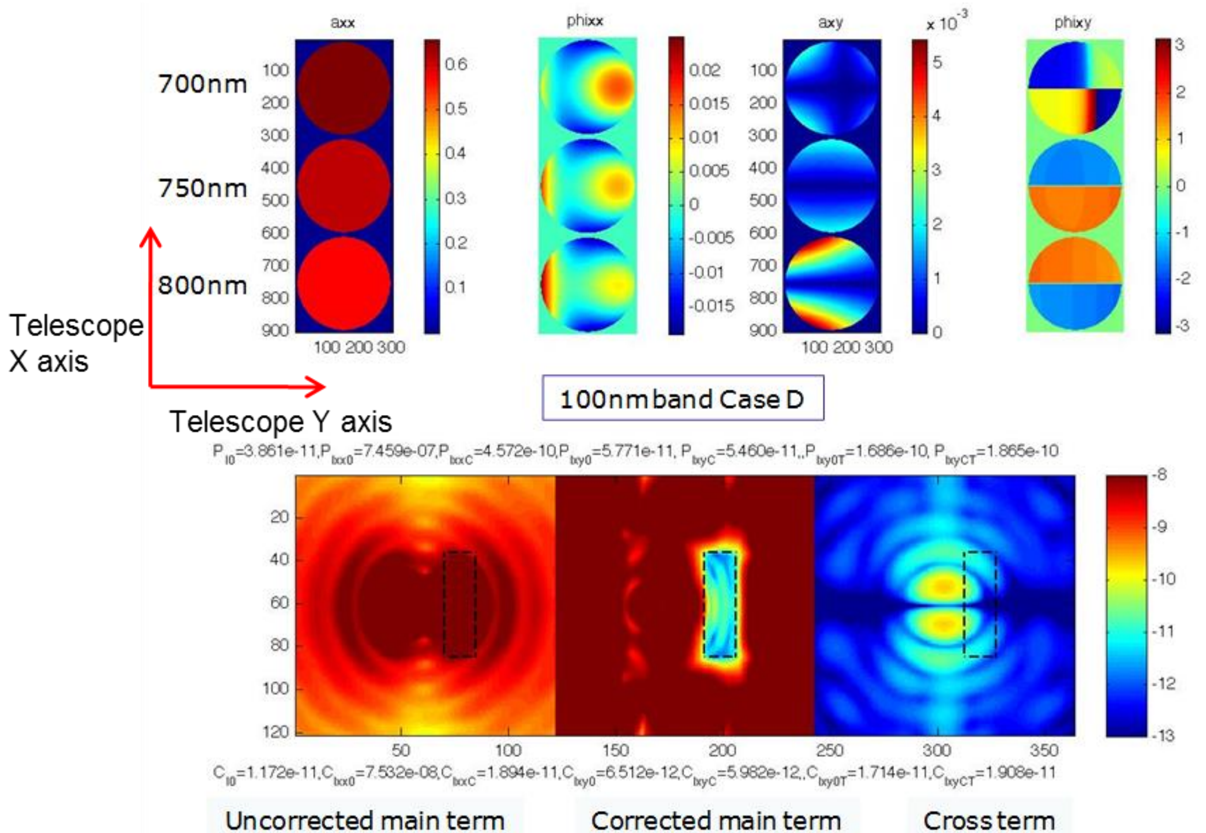

Figure 14. Case D. AlF_3/LaF_3 protected Al mirrors per tables 3 and 4 in the reference below

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