Contamination Effects and Requirements Derivation for the James Webb Space Telescope

Dr. Jonathan Arenberg
Northrop Grumman Space Technology
and
Eve Wooldridge
NASA/Goddard Space Flight Center

With Thanks To ...

The many people who form or support the JWST contamination control team with many hours and many calculations:

Dr. Mark Clampin, Observatory Scientist
Dr. Paul Lightsey, Observatory Optical Systems Engineer

and

From NGST: Robert Lempka, Matthew Macias, Dr. Dan McGregor, Suzanne Casement, Robert Giampaoli, Michael Hirsch

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Mission Requirements Lead to Contamination Requirements

- What is the James Webb Space Telescope (JWST)? What is JWST's mission?
- How does contamination effect the JWST mission, its science performance?
  - Sensitivity
  - Stray Light
  - Transmission
- Derivation of JWST Contamination Requirements

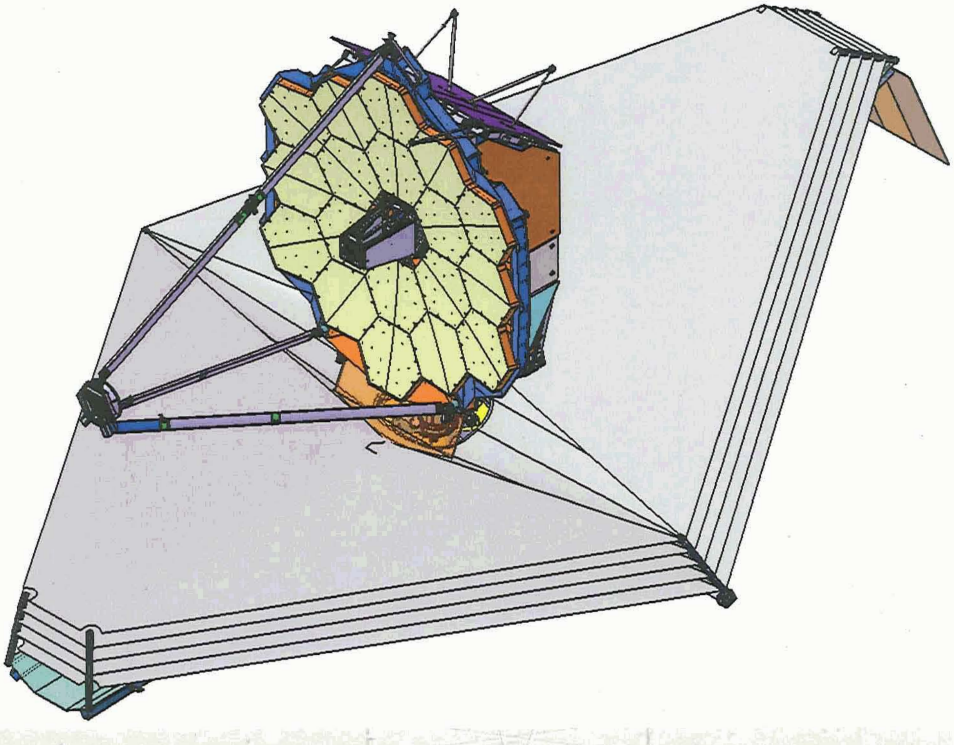
What is JWST? Why is Contamination an Issue?

- **JWST is a large, passively cooled, 6.5 m diameter telescope operating from ~0.6 µm to 29 µm designed to detect First Light in the Cosmic Dark Age, and to**
  - study the reionization initiated by the First Light,
  - the assembly of galaxies,
  - the birth of stars and protoplanetary systems,
  - planetary systems and the origins of life.
- **Passive cooling means an open architecture**
  - Large exposed sensitive areas
- **Detection of First Light leads to the need for the large optical collection area, which must also be very sensitive**
- **Long wavelengths means**
  - telescope is cold, 30-50 K optics temperature
    - need to be very careful about venting and cool-down profile
  - Stray light is a key issue
    - mirrors will require stringent particulate requirement

JWST is Huge

Contamination & Coatings Workshop, 17-19 July 2007

Deployed +J1 View



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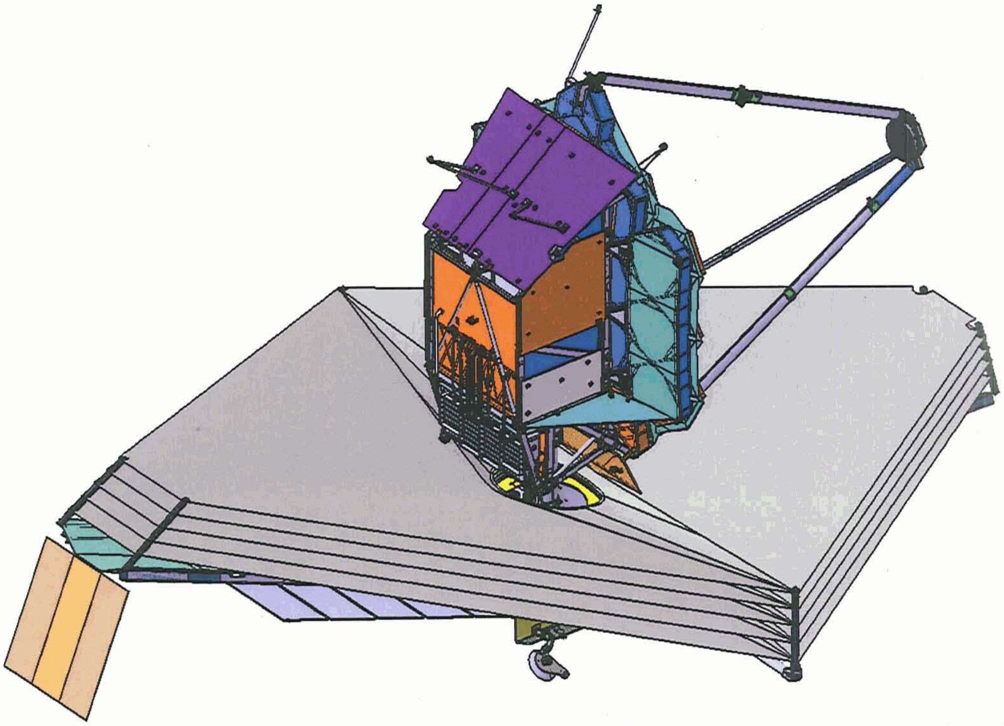
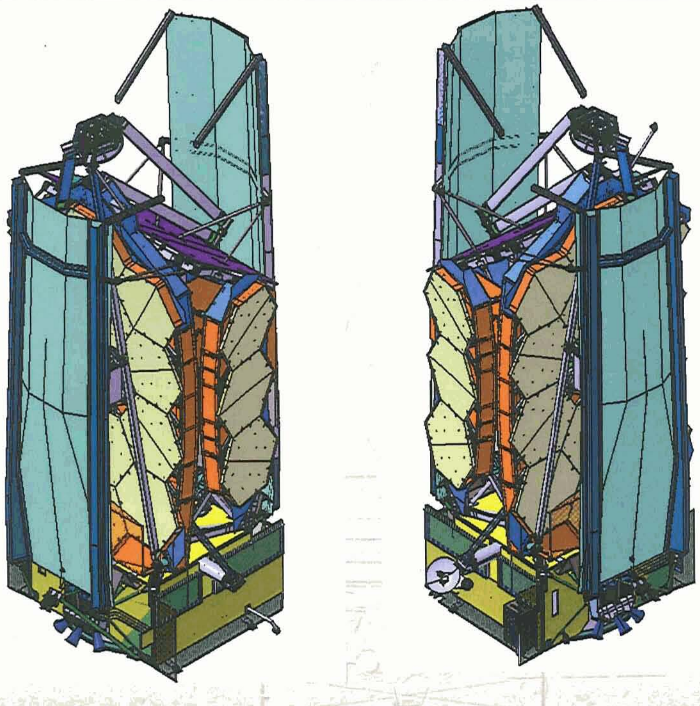
Contamination & Coatings Workshop, 17-19 July 2007

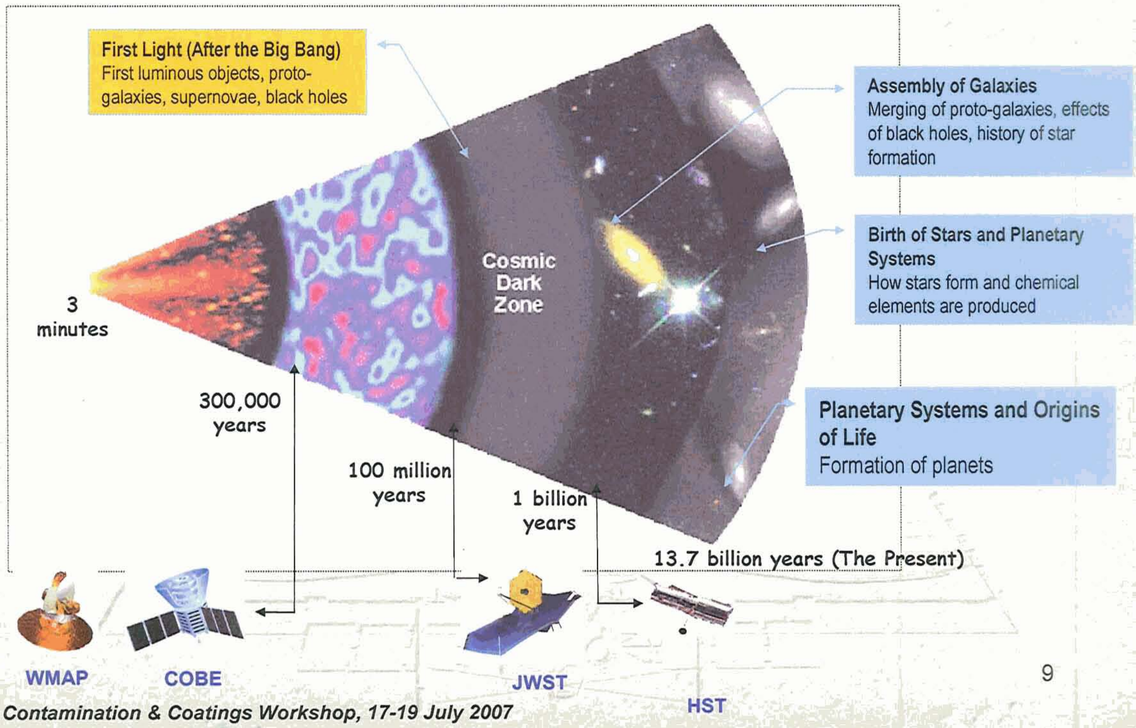
Deployed View



Stowed Views of Baseline 2



JWST's Four Science Themes



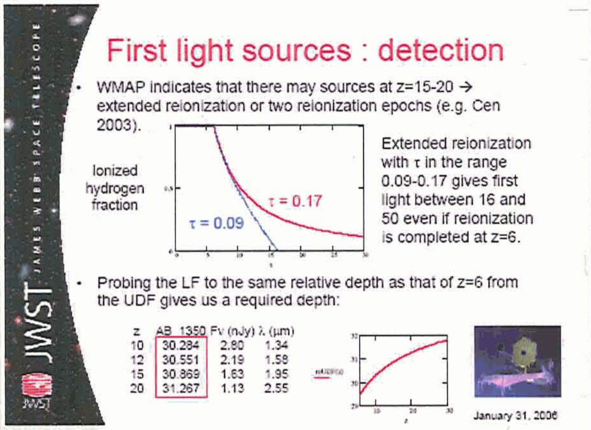
First Light (After the Big Bang)
First luminous objects, proto-galaxies, supernovae, black holes

Assembly of Galaxies
Merging of proto-galaxies, effects of black holes, history of star formation

Birth of Stars and Planetary Systems
How stars form and chemical elements are produced

Planetary Systems and Origins of Life
Formation of planets

Detecting "*First Light*"



First light sources : detection

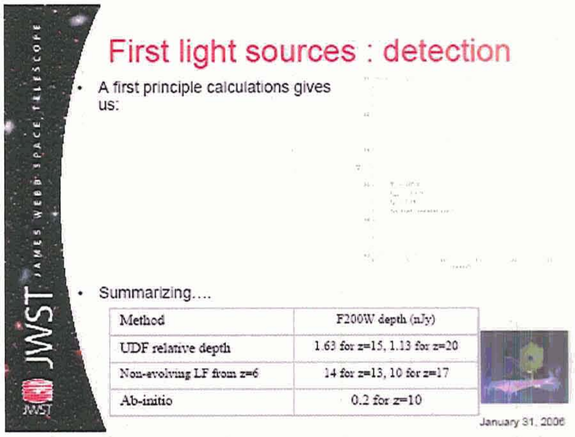
- WMAP indicates that there may sources at z=15-20 → extended reionization or two reionization epochs (e.g. Cen 2003).

Extended reionization with τ in the range 0.09-0.17 gives first light between 16 and 50 even if reionization is completed at z=6.

- Probing the LF to the same relative depth as that of z=6 from the UDF gives us a required depth:

z	AB 1350	Fν (nJy)	λ (μm)
10	30.284	2.80	1.34
12	30.551	2.19	1.58
15	30.869	1.63	1.95
20	31.267	1.13	2.55

January 31, 2006



First light sources : detection

- A first principle calculations gives us:

- Summarizing….

Method	F200W depth (nJy)
UDF relative depth	1.63 for z=15, 1.13 for z=20
Non-evolving LF from z=6	14 for z=13, 10 for z=17
Ab-initio	0.2 for z=10

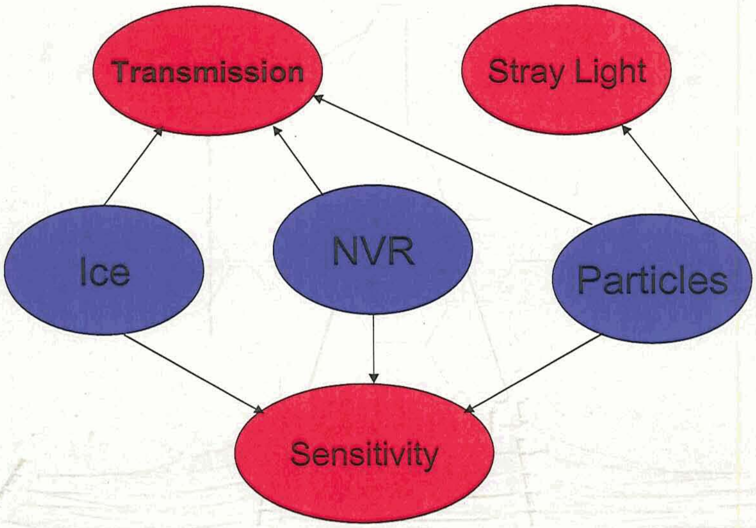
January 31, 2006

From M. Stiavelli et al. JWST SWG, February'06

The time it will take to measure a 1nJy source – that of "First Light" at 2μm to a S/N =10 is sensitive metric of the absolute science performance of the JWST mission.

If stray light exceeds requirements and transmission does not meet requirements, the prime science mission of detecting First Light will be compromised.

How does contamination effect Science Performance?



Transmission

Stray Light

Ice

NVR

Particles

Sensitivity

JWST Mission Requirements

- MR-51
  - Level 2 mission requirement for observatory sensitivity
    - Measured in W/m^{2}Hz for SN and R values
    - Effects the integration time necessary to make an observation
    - Determined by calculation for each instrument; stray light levels and transmission effect sensitivity
- MR-121
  - Level 2 mission requirement for stray light/particulate requirements
    - Stray light spectral radiance level measured in Mega Janskeys (MJy)
      - 1 MJy/sr = 1x10-^{20} W/m^{2}-Hz-sr
    - Particulate contamination increases stray light radiance
- MR-211
  - Level 2 mission requirement for transmission
    - Optical transmission requirement, measured in %
    - The required % transmission accounts for transmission losses from coatings, dust, obscuration, meteoroid damage, and contamination
    - Thin film interference by NVR and water/ice and Percent Area Coverage (PAC) of particulates effect transmission

The Sensitivity Requirement (MR-51)[1]

The observatory system shall reach the sensitivity performance levels shown in the following table when observing a position on the celestial sphere that exhibits 1.2 times the minimum Zodiacal light background power as calculated in the NIRCam, NIRSpec, MIRI, and FGS-TF Sensitivity Calculations.

Wavelength (μm)	Instrument/Mode	Sensitivity
1.15	NIRCam/WFS	1.10 x E-31 $Wm^{-2}Hz^{-1}$ SN=10 in 10.6 s or less & R=4 bandwidth
2	NIRCam	1.14 x E-34 $Wm^{-2}Hz^{-1}$ SN=10 in 10,000 s or less & R=4 bandwidth
3.5	FGS-TF	1.26 x E-33 $Wm^{-2}Hz^{-1}$ SN=10 in 10,000 s or less & R=100 bandwidth
3.0	NIRSpec/Low Res	1.32 x E-33 $Wm^{-2}Hz^{-1}$ SN=10 in 10,000 s or less & R=100 bandwidth
2.0	NIRSpec/Med Res	5.2 x E-22 $Wm^{-2}Hz^{-1}$ SN=10 in 10,000 s or less
10	MIRI/Broad-Band	7.0 x E-33 $Wm^{-2}Hz^{-1}$ SN=10 in 10,000 s or less & R=5 bandwidth
21	MIRI/Broad-Band	8.7 x E-32 $Wm^{-2}Hz^{-1}$ SN=10 in 10,000 s or less & R=4.2 bandwidth
9.2	MIRI/Spectrometer	1.0 x E-20 $Wm^{-2}Hz^{-1}$ SN=10 in 10,000 s or less & R=2400 bandwidth
22.5	MIRI/Spectrometer	5.6 x E-20 $Wm^{-2}Hz^{-1}$ SN=10 in 10,000 s or less & R=2400 bandwidth

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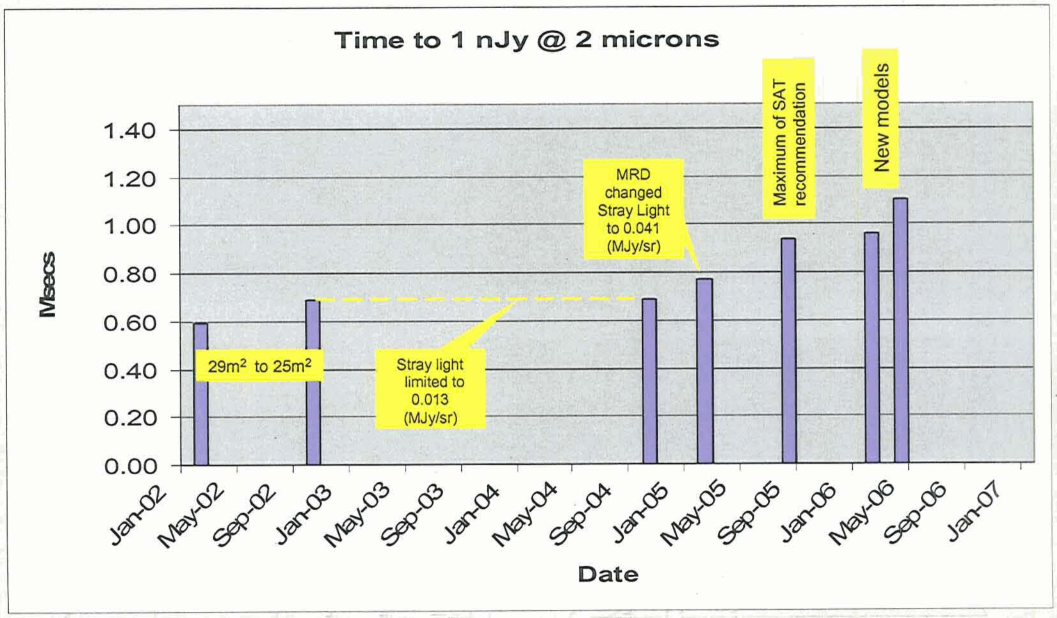
[1] JWST Mission Requirements Document, JWST-RQMT-00634, Revision N, 30 August 2006

History of the changing sensitivity of JWST at 2 micron - mainly due to the increased allocation for stray light


Time to 1 nJy @ 2 microns

Stray Light is a significant source of JWST sensitivity loss for IR Telescopes

- Violation of the stray light requirements has been one of the greatest threats to meeting JWST's sensitivity requirements.
- Contributions to stray light
  - Zodi background (infield)
  - Zodi background (out field)
  - Galactic sky
  - Earth & moon
  - Nearby bright field stars
  - Rogue path

Signal-to-Noise Ratio Depends on Stray Light

$$SNR = \frac{S}{\sqrt{S + Z + SL_{OTE} + SL_{ISIM} + D + Rd}}$$

- S = target signal
- Z = zodiacal background
- SL_{OTE} = stray light background signal from OTE/SC
- SL_{ISIM} = stray light from background signal from ISIM
- D = total integrated dark current
- R = read noise (variance)

The JWST Stray Light Requirement [1]

When observing a position on the celestial sphere that exhibits 1.2 times the minimum Zodiacal light background radiance, the stray light incident into an instrument acceptance cone at the instrument pickoff mirror shall be less than an equivalent background in the field of view having a spectral radiance at the wavelengths and exclusion angles given in the table below.

Radiance (1 x 10^{-20} W/(m^2-Hz-sr)) (MJy/sr)		**Exclusion Angle (degrees)**			
		1.0	0.50	0.25	0.10
Wavelength (µm)	2.0	**0.091**	**0.044**	**0.061**	**0.598**
	3.0	**0.032**	**0.035**	**0.042**	**0.326**

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[1] JWST Mission Requirements Document, JWST-RQMT-00634, Revision N, 30 August 2006

Stray Light as a Function of Cleanliness Level
(March 2006)

Level 550

Wavelength (µm)	In-field Zodi (MJy/sr)	Requirement (MJy/sr)	Galactic Sky (MJy/sr)	Zodi Sky (MJy/sr)	Earth Shine (MJy/sr)	Moon Shine (MJy/sr)	Out-field Total (MJy/sr)
1	0.138	na	0.039	0.029	0.096	0.017	0.181
2	0.094	**0.091**	0.037	0.020	0.054	0.009	**0.120**
3	0.081	**0.032**	0.022	0.008	0.033	0.012	**0.075**
5	0.46	na	0.019	0.001	0.454	0.192	0.666

Level 630

Wavelength (µm)	In-field Zodi (MJy/sr)	Requirement (MJy/sr)	Galactic Sky (MJy/sr)	Zodi Sky (MJy/sr)	Earth Shine (MJy/sr)	Moon Shine (MJy/sr)	Out-field Total (MJy/sr)
1	0.138	na	0.045	0.033	0.115	0.020	0.213
2	0.094	**0.091**	0.046	0.023	0.067	0.012	**0.148**
3	0.081	**0.032**	0.026	0.009	0.036	0.014	**0.085**
5	0.46	na	0.022	0.001	0.480	0.210	0.713

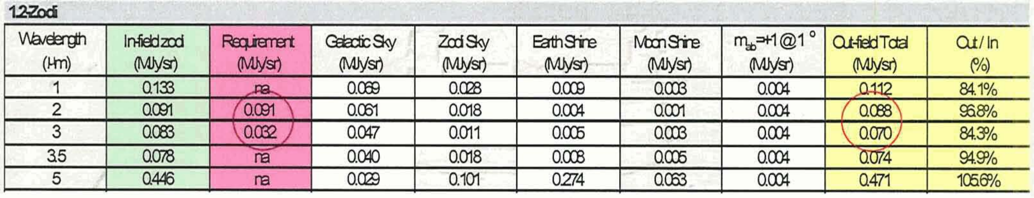
Level 720

Wavelength (µm)	In-field Zodi (MJy/sr)	Requirement (MJy/sr)	Galactic Sky (MJy/sr)	Zodi Sky (MJy/sr)	Earth Shine (MJy/sr)	Moon Shine (MJy/sr)	Out-field Total (MJy/sr)
1	0.138	na	0.062	0.041	0.156	0.028	0.287
2	0.094	**0.091**	0.062	0.029	0.091	0.016	**0.198**
3	0.081	**0.032**	0.034	0.011	0.047	0.018	**0.110**
5	0.46	na	0.027	0.001	0.533	0.244	0.805

The Particulate Requirement

- Further stray light analyses were performed, and from the numbers the senstivity calculated.
- In April 2006, the cleanliness requirement was set at Level 630 (or 1% PAC) for the Primary Mirror (PM) and Secondary Mirror (SM), Level 550 (or 0.5% PAC) for the Tertiary Mirror (TM) and the Fine Steering Mirror (FSM)
- Further stray light analyses have been performed, as design improvements were made

Stray Light as of March 2007 – PM & SM at Level 630, TM and FSM at Level 550



1.2-Zodi

Wavelength (μm)	In-field zodi (MJy/sr)	Requirement (MJy/sr)	Galactic Sky (MJy/sr)	Zodi Sky (MJy/sr)	Earth Shine (MJy/sr)	Moon Shine (MJy/sr)	m_{ab}=+1 @1° (MJy/sr)	Out-field Total (MJy/sr)	Out / In (%)
1	0.133	na	0.069	0.028	0.009	0.003	0.004	0.112	84.1%
2	0.091	0.091	0.061	0.018	0.004	0.001	0.004	0.088	96.8%
3	0.083	0.032	0.047	0.011	0.005	0.003	0.004	0.070	84.3%
3.5	0.078	na	0.040	0.018	0.008	0.005	0.004	0.074	94.9%
5	0.446	na	0.029	0.101	0.274	0.063	0.004	0.471	105.6%

Earth at 30.5 ¡ Moon at 45.5 ¡

Most Recent Revision

- Prediction of particulate level at time of launch indicated that to meet 1% PAC on the Primary Mirror, aggressive mirror covering techniques would be required – very undesirable to optics group
- The same analysis predicted that 1.4% EOL could be met without extreme protective measures
- Systems engineering evaluated relaxing the requirement to 1.5% PAC on the Primary Mirror, and tightening the requirement to 0.5% PAC on the Secondary Mirror
  - The PM is integrated cup-up, is very large and is segmented, therefore it is much harder to maintain clean
  - This change would minimize risk and cost

Analyses Performed on 3 Cases

		Baseline (SDR4) PM SM PAC 1% TM FSM 0.5%		Alternatives			
				Case1	Case 2	Case 3	
Rank	Path	%	MJ/sr	MJ/sr	MJ/sr	MJ/sr	Comments
1	FPA*-POM-FSM-TM-SM-SKY	33.58%	0.026528	0.026528	0.000000	0.000000	Case 2 and 3 assume elimination of truant path by PM closeouts
2	FPA*-POM-FSM-TM-SM-PM-SKY	10.43%	0.00824	0.01236	0.01236	0.012360	Case 1 assumes increase of PM dust PAC to 1.5%
3	FPA*-POM-FSM-TM-SM-PM closeout-SKY	9.53%	0.007529	0.007529	0.015057	0.015057	Case 2 and 3 double the contributions for the larger PM closeouts
4	FPA*-POM-FSM-TM-SM-PM-SMST-SKY	7.29%	0.005759	0.005759	0.005759	0.005759	
5	FPA*-POM-FSM-TM-SM-PM-SKY	6.83%	0.005396	0.002698	0.002698	0.002698	Case 1 decreases SM dust PAC to 0.5%
6	FPA*-POM-FSM-TM-SM-SKY	4.95%	0.003911	0.001955	0.001955	0.001955	Case 1 descrease SM dust PAC to 0.5%
7	FPA*-POM-FSM mask-TM-SM-SKY	4.74%	0.003745	0.003745	0.003745	0.000000	Case 3 assumes scatter from FSM Mask is eliminated
8	FPA*-POM-FSM-TM-SM-SS-SKY	3.87%	0.003057	0.003057	0.003057	0.003057	
9	FPA*-POM-FSM-TM-SM-PM-SKY	2.02%	0.001596	0.001596	0.001596	0.000000	Case 3 assumes scatter from FSM is eliminated
10	FPA*-POM-FSM-TM-SM-AOS Bench-SKY	1.98%	0.001564	0.001564	0.001564	0.000000	Case 3 assumes scatter from AOS bench is eliminated
11	FPA*-POM-FSM mask-TM-SM-SS-SKY	1.45%	0.001146	0.001146	0.001146	0.000000	Case 3 assumes scatter from FSM Mask is eliminated
12	FPA*-POM-FSM-TM-SM-PM baffle center-SKY	1.33%	0.001051	0.001051	0.001051	0.000000	Case 3 assumes scatter from PM Baffle is eliminated
13	FPA*-POM-FSM-TM-SM-PM-SKY	1.04%	0.000822	0.000822	0.000822	0.000822	
14	FPA*-POM-FSM-TM-SM-SS-SKY	0.82%	0.000648	0.000324	0.000324	0.000324	
15	FPA*-POM-FSM-TM-SM-PM-SMST-SKY	0.79%	0.000624	0.000624	0.000624	0.000000	
16	FPA*-POM-FSM-TM-SM-PM-SKY	0.70%	0.000553	0.000553	0.000553	0.000553	
17	FPA*-POM-FSM-TM-SKY	0.70%	0.000553	0.000553	0.000553	0.000553	
18	FPA*-POM-FSM-TM-SM-PM-SMST-SS-SKY	0.57%	0.00045	0.00045	0.00045	0.000450	
19	FPA*-POM-SKY	0.50%	0.000395	0.000395	0.000395	0.000395	
20	FPA*-POM-FSM mask-TM-SKY	0.47%	0.000371	0.000371	0.000371	0.000000	Case 3 assumes scatter from FSM Mask is eliminated
21	Residual	6.41%	0.005064	0.005064	0.005064	0.005064	
	Total	**100.00%**	**0.079000**	**0.078143**	**0.059143**	**0.049047**	

Case 1: Relax PAC on Primary Mirror to 1.5% and tighten SM contamination to 0.5%

Case 2 Find PM closeout geometry that eliminates truant path, and assume the scatter from these closeouts increases by factor of 2

Case 3: Eliminate via proper baffling scattered paths from FSM Mask, PM Baffle, SMST, etc

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The Current Particulate Requirement

- **Improvements to design (i.e. closeouts to stray light paths) and the combination of tightening SM requirement while relaxing PM requirement led to the following, most current requirements:**

Primary Mirror	**1.5 %PAC**
Secondary Mirror	**0.5 %PAC**
Fine Steering Mirror	**0.5 %PAC**
Tertiary Mirror	**0.5 %PAC**

- **Systems engineering put conditions on these changes:**
  - Stray Light and Transmission levels *remain* at their current required levels (no relaxation permitted for easing particulate requirement)
  - Design features to improve stray light performance must continue to be pursued
  - The analyses used to accept the change is correct and does not change significantly in the next round of analyses
  - No degradation of the OTE transmission error budget is incurred because of this change

The Transmission Budget

Equally critical to Observatory Sensitivity …

The Transmission Requirement (MR-211)[1]

Accounting for all effects on mirror transmission including: coatings, dust, obscuration, meteoroid damage, and contamination, the End of Life (EOL) optical spectral transmission of the OTE shall be greater than the values shown in the following table for wavelengths between 0.8 micrometers and 2.0 micrometers, and greater than 88% for wavelengths from 2.0 micrometers to 27 micrometers, with transmission out to 29 micrometers as a goal.

Wavelength (μm)	**Transmission** τ (%)
0.8	**61.5**
1.5	**82.0**
2.0	**88.0**
>2.0	**88**

[1] JWST Mission Requirements Document, JWST-RQMT-00634, Revision N, 30 August 2006

Signal Level is Dependent on Transmission

$$S = F_\nu \cdot \Delta\nu \cdot \tau_{ote} \cdot A \cdot \tau_{instr} \cdot QE \cdot t_{\exp} / (h \cdot \nu)$$

$$S = F_\lambda \cdot \Delta\lambda \cdot \tau_{ote} \cdot A \cdot \tau_{instr} \cdot QE \cdot t_{\exp} \cdot \lambda / (h \cdot c)$$

- **Signal calculation given for either frequency or wavelength spectral irradiances**
  - F_ν = spectral irradiance (per frequency)
  - F_λ = spectral irradiance (per wavelength)
  - $\Delta\nu$ = spectral bandwidth (frequency)
  - $\Delta\lambda$ = spectral bandwidth (wavelength)
  - texp = total integration time (100,000 seconds)
  - A = collecting aperture area
  - τ_{OTE} = transmittance of the OTE optics
  - τ_{instr} = transmittance of the instrument
  - QE = quantum efficiency of detector
  - ν = frequency
  - λ = wavelength
  - h = Planck's constant
  - c = speed of light

NVR and Water/Ice Significant Source of Transmission Loss for JWST

Ice Primer: Ice Absorbs Light

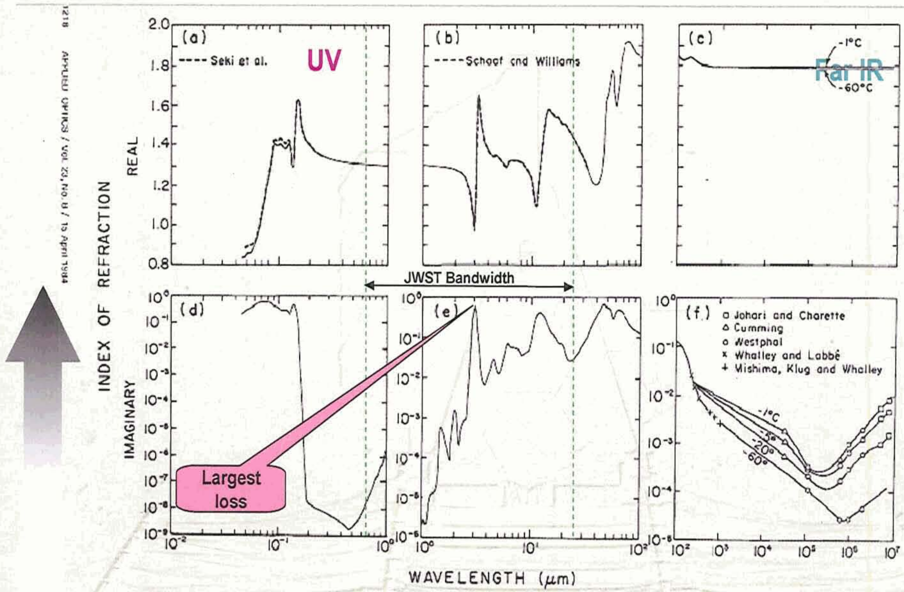


Fig. 11. Compilation of real (a)–(c) and imaginary (d)–(f) parts of the refractive index of ice Ih at $T = -7°C$ for $\lambda < 167$ μm and at four temperatures for $\lambda > 167$ μm. Data sources and uncertainties are discussed in the text. These graphs are tabulated in Tables I and II. The dashed line in (a) shows the results of Seki *et al.*[7] which differ from our compilation as discussed in Sec. IX of the text. The dashed line in (b) similarly shows the results of Schaaf and Williams.[10] In (f) the curves are a subjective interpolation between the data points shown.

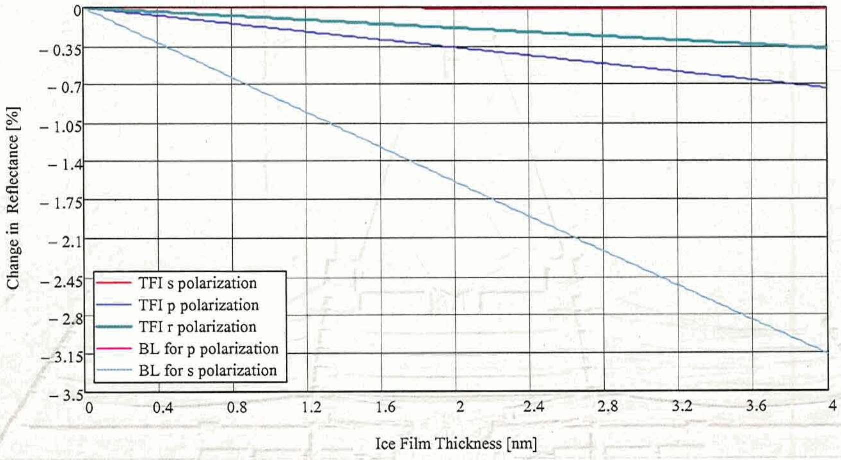
From Warren (1984)

Integrated Telescope Transmission Calculation

- Calculate the transmission for each mirror
- Reflectance using a contamination and ice modified stack
  - Angle of incidence effects
- PAC for each mirror
- Both polarizations

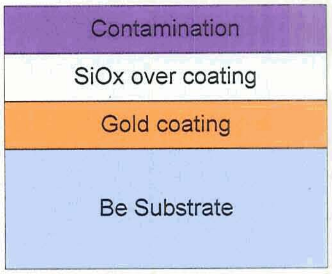
Beer is Not a Good Idea (At least for this application)

- Beer's Law ignores almost all of the physics going on
  - Polarization
  - Multiple reflections
  - Protective layer



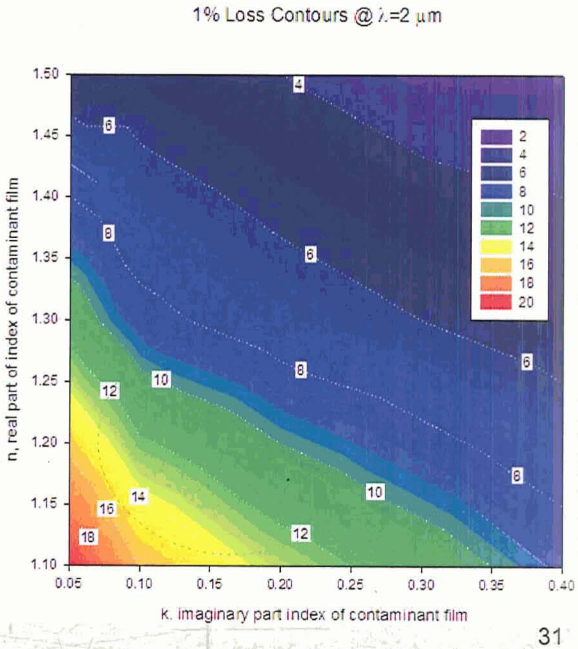
Thin Film Calculations

- The mirror (clean or contaminated) is treated as a system of films on a gold substrate
- The reflectance depends on
  - Optical properties of the gold, SiOx and the contamination
    - Complex index of refraction
      - Gold and SiOx (SiO2) from Palik
      - Ice from Warren
      - NVR-"literature"
  - Angle of incidence, polarization and wavelength of the incident light
- Have calculation of mirrors (thin film analysis) that includes all of the above effects
- Mathcad file
- Used to calculate reflectance of mirrors at various AOI, ice and NVR films



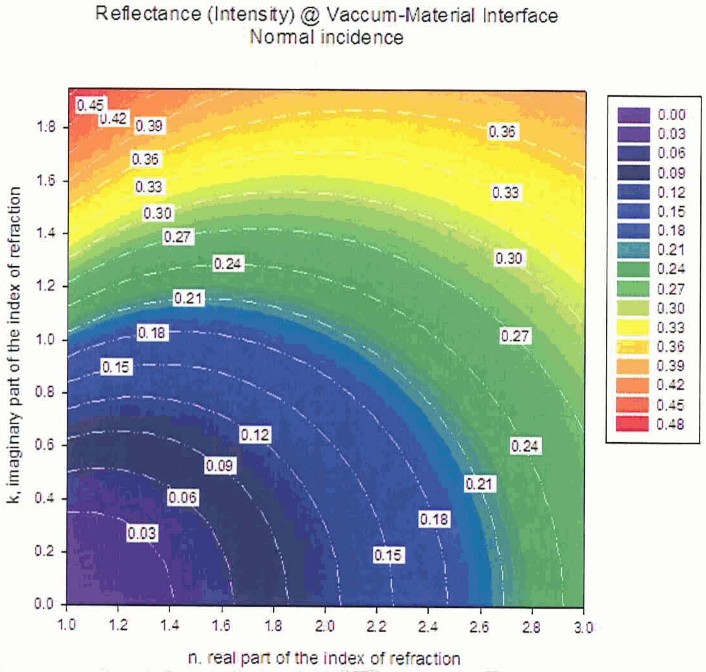
NVR Impact is Hard to Assess

- Since the indices of NVR is specific to the species and the species are unknown, so are the relevant n and k values
- Inserted n and k for an NVR layer in the TFI calculation and determined the thickness to lose 1% reflectance at normal incidence
- From the literature, we can assume and likely species have an n and k in the green circle
  - ~ 8 nm thickness for 1% loss
  - Assume 1.2 g/cc density
  - 1 mg/cm2→ Level A



1% Loss Contours @ λ=2 μm

Reflection at Vacuum Material Interface



Reflectance (Intensity) @ Vaccum-Material Interface
Normal incidence

Table of Contamination Requirements in the CCP

Table I. EOL Cleanliness Requirements for OTE Mirrors

Mirror	Particulate (Percent Area Coverage, PAC)	Molecular (angstroms, Å)	Water Ice (angstroms, Å)	Amorphous Carbon (angstroms, Å)
PM (2)	1.0 (TBR)	200 (TBR) (1)	200 (TBR)	50 (TBR)
SMA	1.0 (TBR)	200 (TBR) (1)	200 (TBR)	50 (TBR)
TMA	0.5	200 (TBR) (1)	100 (TBR)	N/A
FSM	0.5	200 (TBR) (1)	0 (TBR)	N/A

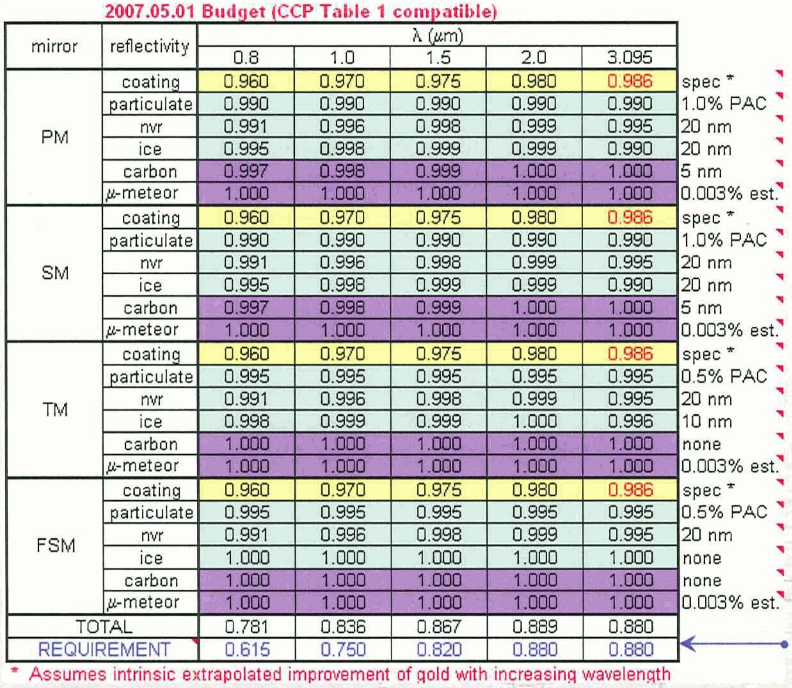
(1) 200 Angstroms is equivalent to Level B per IEST-STD-CC1246D assuming a uniform molecular film of unit density. For conversions, refer to Appendix D.

(2) The values specified for the OTE Primary Mirror are representative of an average of the 18 PMSAs.

PM now 1.5%, SM now 0.5%

EOL Transmission Budget

2007.05.01 Budget (CCP Table 1 compatible)



mirror	reflectivity	λ (µm)					
		0.8	1.0	1.5	2.0	3.095	
PM	coating	0.960	0.970	0.975	0.980	0.986	spec *
	particulate	0.990	0.990	0.990	0.990	0.990	1.0% PAC
	nvr	0.991	0.996	0.998	0.999	0.995	20 nm
	ice	0.995	0.998	0.999	0.999	0.990	20 nm
	carbon	0.997	0.998	0.999	1.000	1.000	5 nm
	µ-meteor	1.000	1.000	1.000	1.000	1.000	0.003% est.
SM	coating	0.960	0.970	0.975	0.980	0.986	spec *
	particulate	0.990	0.990	0.990	0.990	0.990	1.0% PAC
	nvr	0.991	0.996	0.998	0.999	0.995	20 nm
	ice	0.995	0.998	0.999	0.999	0.990	20 nm
	carbon	0.997	0.998	0.999	1.000	1.000	5 nm
	µ-meteor	1.000	1.000	1.000	1.000	1.000	0.003% est.
TM	coating	0.960	0.970	0.975	0.980	0.986	spec *
	particulate	0.995	0.995	0.995	0.995	0.995	0.5% PAC
	nvr	0.991	0.996	0.998	0.999	0.995	20 nm
	ice	0.998	0.999	0.999	1.000	0.996	10 nm
	carbon	1.000	1.000	1.000	1.000	1.000	none
	µ-meteor	1.000	1.000	1.000	1.000	1.000	0.003% est.
FSM	coating	0.960	0.970	0.975	0.980	0.986	spec *
	particulate	0.995	0.995	0.995	0.995	0.995	0.5% PAC
	nvr	0.991	0.996	0.998	0.999	0.995	20 nm
	ice	1.000	1.000	1.000	1.000	1.000	none
	carbon	1.000	1.000	1.000	1.000	1.000	none
	µ-meteor	1.000	1.000	1.000	1.000	1.000	0.003% est.
TOTAL		0.781	0.836	0.867	0.889	0.880	
REQUIREMENT		0.615	0.750	0.820	0.880	0.880	

* Assumes intrinsic extrapolated improvement of gold with increasing wavelength

Coating specification
Contamination Control Plan
flight environment degradation

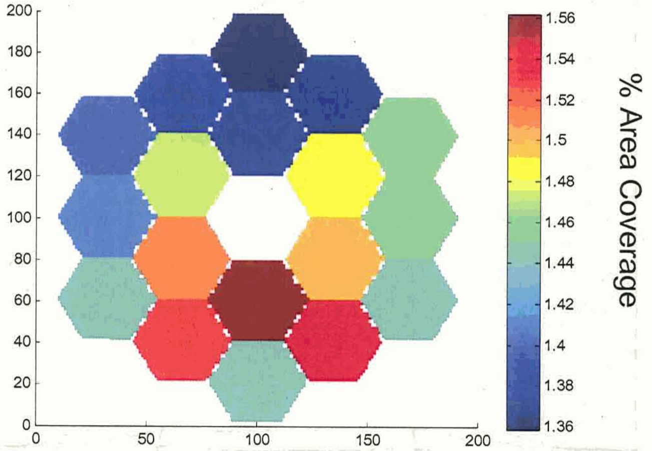
- Coating based on SBMD measured data
- Particulates and NVR based on contamination control modeling anchored to past experiences
- Ice based on preliminary analyses based on thermal cool-down modeling and anticipated water content of materials at launch. These analyses are being refined.
- Carbon is a conservative estimate based on similar data obtained from GOES
- Micrometeoroid data based on L2 environment and hypervelocity testing of mirror samples

MR-211/OBS-102

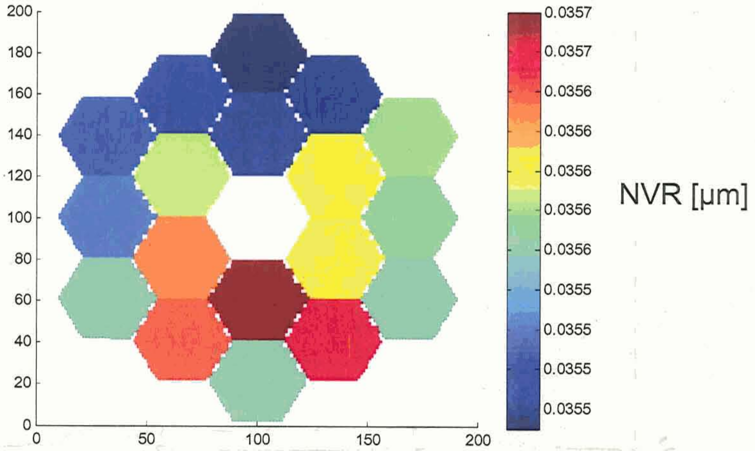
Particulate Coverage is Estimated from Schedule

- For each stage of I&T the duration and location of activities is known
- Using an estimate (requirement) of allowed fallout the incremental increase in percent areal coverage (PAC) is determined
- The main effects of particulate coverage is in loss of transmission
  - Wavelength independent
- The AI&T schedule gives a prediction of the pre-launch particulate load on each mirror
- A redistribution analysis is also conducted to see where the particles are likely to be after launch

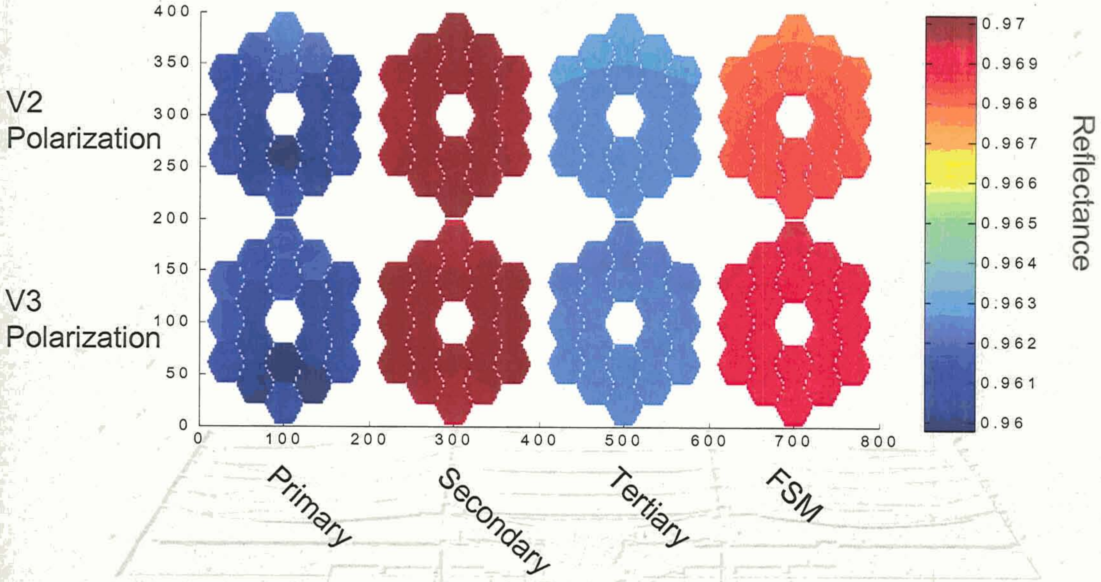
PMSA PAC Contamination



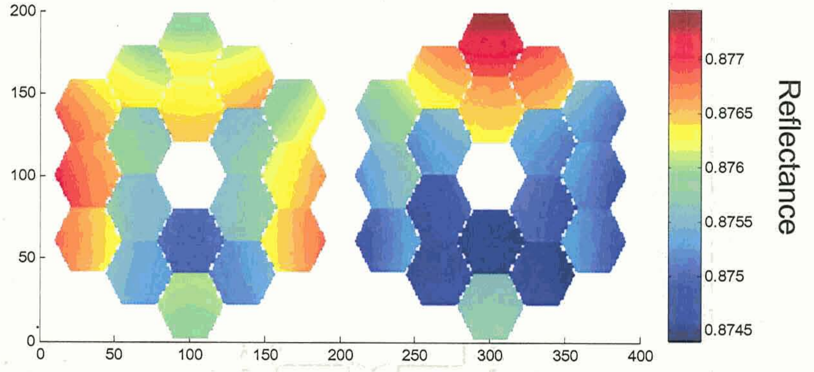
PMSA NVR Contamination



Dirty Mirrors

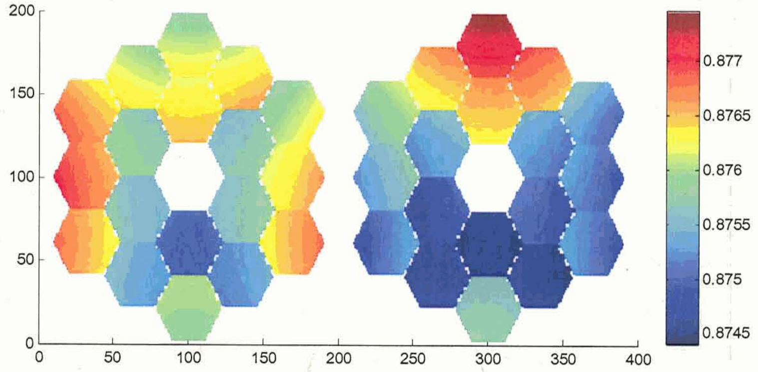


Telescope Throughput



V2 Polarization V3 Polarization

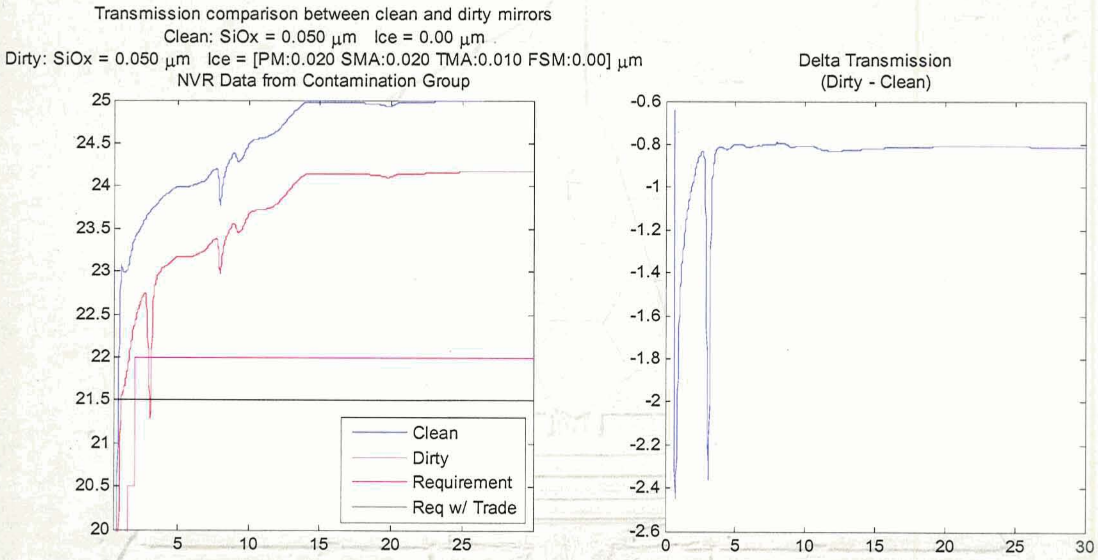
Integrated Telescope Transmission Calculation



V2 Polarization V3 Polarization

- Calculate the transmission for each mirror
- Reflectance using a contamination and ice modified stack
  - Angle of incidence effects
- PAC for each mirror
- Both polarizations

Wavelength Sweep



Summary

- **JWST is a challenging mission in all respects**
- **Science performance is sensitive to contamination levels**
- **Mission demands open architecture**
- **Open architecture places greater emphasis on contamination requirements**
- **Contamination requirements established are directly derived from the Mission requirements**