THROUGHPUT DEGRADATION TECH NOTE

Addendum to TMT Throughput Budget

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Prepared By:

\signature on file\

Bart Fordham
TMT Systems Engineer

Concurrence:

\signature on file\

Gelys Trancho
TMT Systems Engineering
Group Leader

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1. INTRODUCTION

1.1 INTRODUCTION

Mirror degradation due to coating tarnishing and dust accumulation is a significant issue for any optical observatory. The impact on throughput, in extreme cases, can severely limit the science that can be achieved by the instruments of the telescope due to the non-linear effect on throughput across the wavelength range. To remediate reduced reflectivity, cleaning (whether in-situ or removed) and recoating procedures need to be undertaken on the optical surfaces. The frequency of these processes is highly dependent on the coating type and the environment within which the mirrors exist.

Prior experience from other observatories has given a solid knowledge foundation regarding cleaning and coating processes. However, the results obtained for throughput and reflectivity by these other observatories are often applied without taking into consideration local configurations or environment. This technical note uses a numerical approach, to better approximate the required cleaning frequency for TMT.

1.2 PURPOSE

The purpose of this document is to describe the method for calculating throughput for the TMT Observatory at the telescope level (not inclusive of AO or instruments), as applied within RD4, TMT Throughput Budget. These calculations apply real-world data from Gemini North to determine realistic performance measures.

1.3 SCOPE

This document is relevant only to REL02 of the TMT Throughput Budget (RD4) – prior versions served to collect requirement values and estimate the instrument throughput via those values. The calculations in this document only consider the telescope itself, in the absence of instruments and adaptive optics. Assumptions and estimations are only relevant to the Mauna Kea site, and Gemini 4-layer protected silver coating recipe.

1.4 APPLICABLE DOCUMENTS

N/A

1.5 REFERENCE DOCUMENTS

Reference documents are informational, and are not directly binding.

RD1 Gemini Optics Reflectivity Data, (TMT.OPT.COR.15.003)

RD2 Gemini Coating Specification - Informal, (TMT.OPT.SPE.09.003)

RD3 Telescope Throughput Over Time Calculator, (TMT.OPT.ECR.09.006)

RD4 TMT Throughput Budget, (TMT.SEN.TEC.16.087)

RD5 Deleted

RD6 Observatory Architecture Document, (TMT.SEN.DRD.05.002)

1.6 ABBREVIATIONS

AO – Adaptive Optics

CO2 – Carbon Dioxide

CTIO – Cerro Tololo Astronomical Observatory

GN – Gemini North

IR – Infrared

M1 – Primary Mirror

M2 – Secondary Mirror

M3 – Tertiary Mirror

NIR – Near-Infrared (typically 1-2.5 microns wavelength)

SPIE – International Society for Optical Engineering

TMT – Thirty Meter Telescope

WFOS – Wide Field Optical Spectrograph

2. THROUGHPUT CALCULATION

2.1 REFLECTIVITY DATA

2.1.1 Gemini 4-Layer Recipe

The dual Gemini telescopes have evaluated the performance of multi-layer silver-based mirror coatings during the last two decades. The optimal protected Ag 4-layer coating is used at Gemini for it's high reflectivity above 400nm wavelength, and durability in a tarnishing environment. This is the baseline mirror coating for TMT, with reflectivity measurements for fresh coatings provided in this section. A spectrophotometer is used for fresh coating reflectivity measurement.

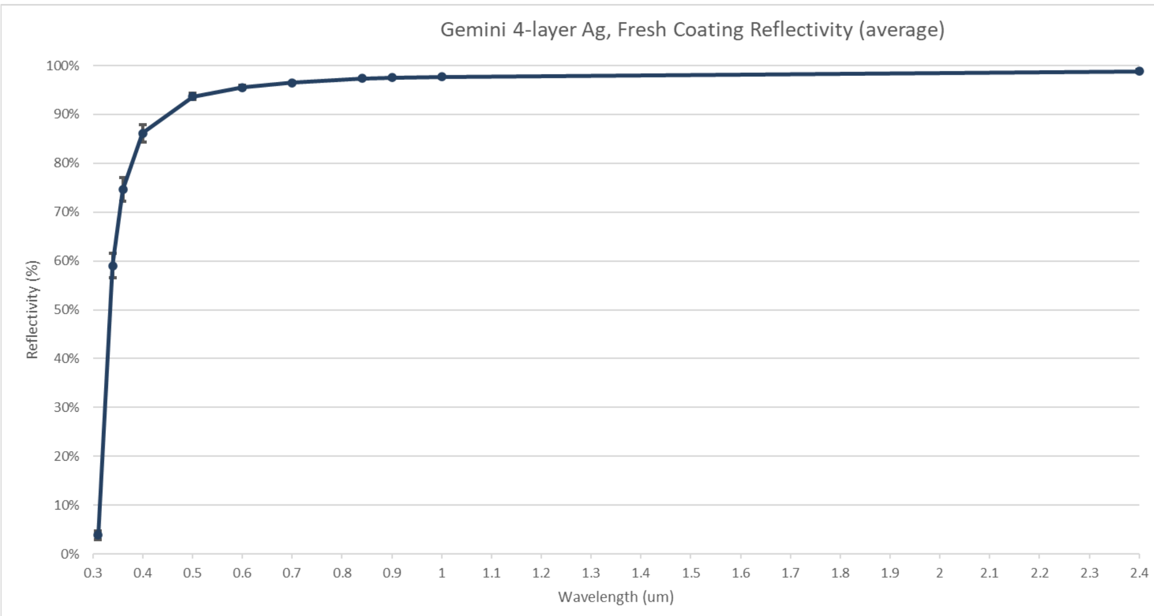

Figure 2-1 - Gemini 4-layer fresh coating data in the visible spectrum, average with standard deviation.

2.1.2 Throughput Degradation Rates

To estimate the TMT throughput degradation over time, data from Gemini North is used to determine the average degradation rate. The available data is wavelength dependent, allowing this estimate to be more appropriate than prior calculations which simply applied either a guesstimate percentage loss linearly across the wavelength range, or data from coated samples – not the actual GN M1 mirror.

Only GN data is used due to it's location at Mauna Kea and use of the 4-layer Ag coating. No other observatory's data is included in the calculation of degradation rate, as coating type and location effects (including dust profile, wind and dust events, local temperature and humidity, mirror sample dust accumulation anomalies) have a significant effect on throughput as is well known.

The equipment used to collect data regularly at Gemini is a reflectometer, which takes reflectivity measurements at four wavelengths - 470, 530, 650, and 880nm. For our purposes here, inner linear interpolation and extrapolation is used to find other points along the visible, NIR and IR spectrum.

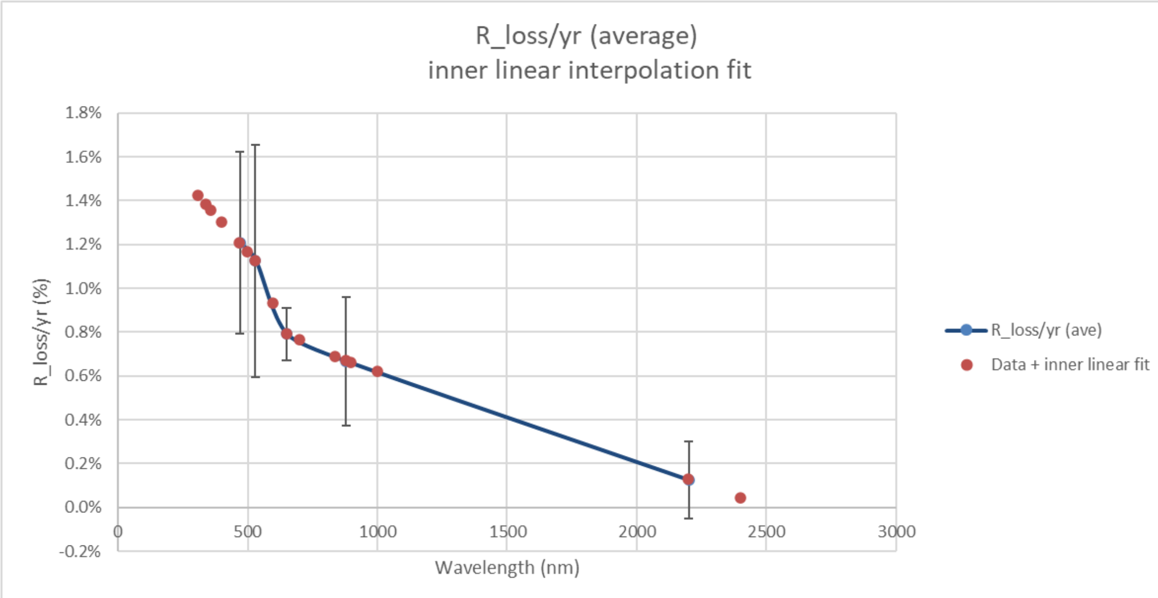

Figure 2-2 - GN M1 reflectivity loss per year, with interpolation and with data points <470nm and >2200nm extrapolated. Standard deviation on data points included as error bars.

Commonly reported is the susceptibility of shorter wavelengths to throughput degradation over time – this is represented by the above plot. This degradation curve is applied to the fresh coating values to estimate the TMT throughput degradation over time. Note that the available data is inclusive of both coating corrosion and dust accumulation – however it is noted in various SPIE papers that the Gemini 4-layer coating exhibits almost no coating corrosion, and hence throughput degradation is, in this case, dominated by dust accumulation.

2.2 ASSUMPTIONS

To estimate TMT telescope throughput over time, several assumptions need to be made:

- Fresh coating data for the Gemini 4-layer recipe are aggregated from RD1
- Reflectivity loss due to dust accumulation are aggregated from RD1 and RD2
- Calculations for reflectivity loss are based on wavelength dependency
- Coating corrosion negligible for Gemini 4-layer recipe
- CO2 cleaning effect is averaged linearly over time – negating any seasonal effects
    - Assumed Gemini North CO2 cleaned consistently once per week
- CO2 snow clean gain is linear across wavelength (see Appendix 3.4)
    - Assumed CO2 clean gain of 50%
- Assumed all three mirrors are CO2 snow cleaned
- M1 reflectivity is assumed to be an average of all segment ages of coatings
- Assumes every mirror is recoated every two years (inclusive of M2 and M3)
- Assumed M2 and M3 degrade at same rate as M1

- Assumes zero recoating stagger (time difference between M2 and M3 coating)
- Assumes no wet washing of any mirror
- Two year period only investigated – no reflectivity loss per strip and recoat operation considered

2.3 Error Sources

Fresh Coating

- Statistical error of fresh coating reflectivity's due to averaging small number of data sets
- Measurement precision of Cary 500 and Cary 5000 spectrophotometers used to measure fresh coatings
    - Less reliable numbers at greater than ~2500nm

Throughput Degradation Rate

- Statistical error of throughput degradation rate due to averaging small number of data sets
- Interpolation errors due to reflectivity loss being measured at only 470, 530, 650, 880, 2200nm wavelengths
- Extrapolation error below 470nm and above 2200nm (shorter wavelengths more susceptible to degradation)
- Measurement precision of reflectometers used to measure throughput over time (two separate devices for visible and IR)
- Applying CO2 clean gain of 50% for each clean, to extrapolate different cleaning schedules

Calculation uncertainty is greatest at wavelengths <500nm, due to sensitivity to degradation there, and data fitting / extrapolation at these short wavelengths. Extrapolation error in reflectivity loss rate is likely to dominate all error sources.

2.4 TMT Throughput Over Time

The throughput over time is estimated, to determine feasibility of maintaining throughput via regular frequency of CO2 snow cleanings. The throughput is calculated as a function of fresh coating total throughput (M1 times M2 times M3), minus the degradation per month (applied as a percentage linearly). Clearly as CO2 cleaning recovers a proportion of mirror reflectivity, there is a relationship between each mirror's reflectivity over time and the overall telescope throughput over time with the cleaning frequency and coating age as variables. The coating age is equivalent to number of weeks since last fresh coating.

Four different scenarios for cleaning frequency and coating age are investigated:

1. Weekly CO2 cleaning of M1, M2 and M3 with degradation set equivalent to a coating age of 52 weeks for each mirror (i.e. M2/M3 coated once per year and 10 M1 segments coated twice per month)
2. **Baseline TMT scenario**: Biweekly (twice per month) CO2 cleaning for each mirror, average coating age 52 weeks for each mirror (M2/M3 coated once per year and 10 M1 segments coated twice per month, all M1 segments coated in 2 years)
3. Monthly CO2 clean, average coating age of M1 52 weeks, coating age of 26 weeks for both M2 and M3 ((i.e. M2/M3 coated once per year and 10 M1 segments coated twice per month)

4. Monthly CO2 clean, with coating age of 52 weeks for M1, M2 and M3 (i.e. M2/M3 coated **twice** per year and 10 M1 segments coated twice per month)

As the aim with any telescope is to maintain as much throughput as possible (within the bounds of appropriate maintenance cost and operational time), there is no hard and fast performance measure. The trade-off is performed at a project level, and hence no throughput loss limit is plotted.

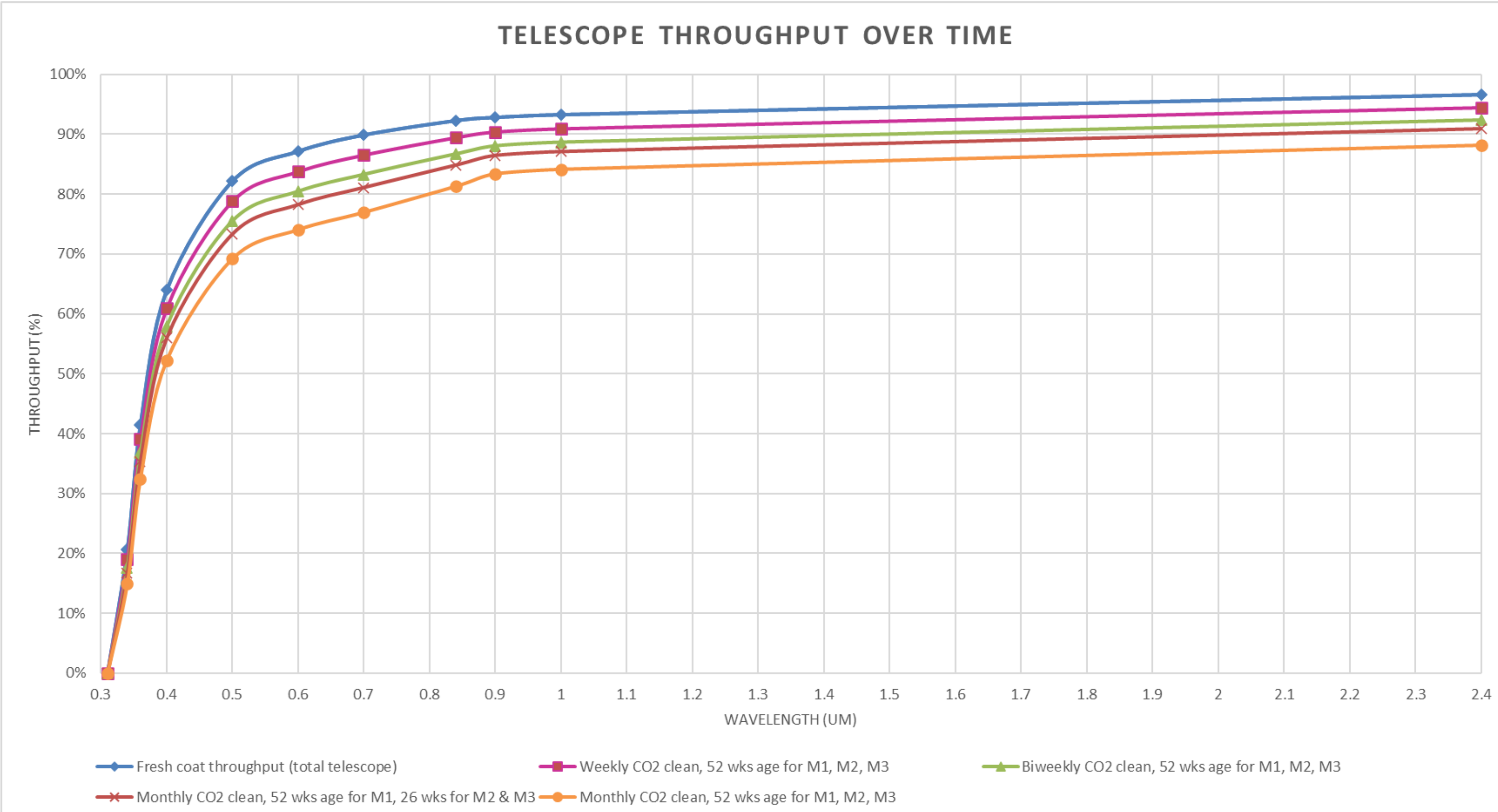

Figure 2-3 - TMT estimated total throughput over time (M1, M2 and M3 combined), four cleaning scenarios applied to Gemini 4-layer recipe fresh coating.

Table 2-1. Tabulated data for Figure 2-3 "Telescope Throughput Over Time".

	Wavelength (um)										
	0.31	**0.34**	**0.36**	**0.4**	**0.5**	**0.6**	**0.7**	**0.84**	**0.9**	**1**	**2.4**
Fresh coat throughput (total telescope)	0.0%	20.6%	41.5%	64.0%	82.2%	87.2%	89.9%	92.3%	92.8%	93.3%	96.6%
Weekly CO2 clean, 52 wks age for M1, M2, M3	0.0%	19.0%	39.1%	60.9%	78.8%	83.8%	86.5%	89.5%	90.4%	90.9%	94.5%
Biweekly CO2 clean, 52 wks age for M1, M2, M3	0.0%	17.6%	36.8%	57.9%	75.5%	80.4%	83.3%	86.7%	88.0%	88.6%	92.3%
Monthly CO2 clean, 52 wks age for M1, 26 wks for M2 & M3	0.0%	16.7%	35.3%	56.0%	73.3%	78.3%	81.1%	84.9%	86.5%	87.1%	90.9%
Monthly CO2 clean, 52 wks age for M1, M2, M3	0.0%	14.9%	32.5%	52.3%	69.2%	74.1%	77.0%	81.3%	83.4%	84.1%	88.2%

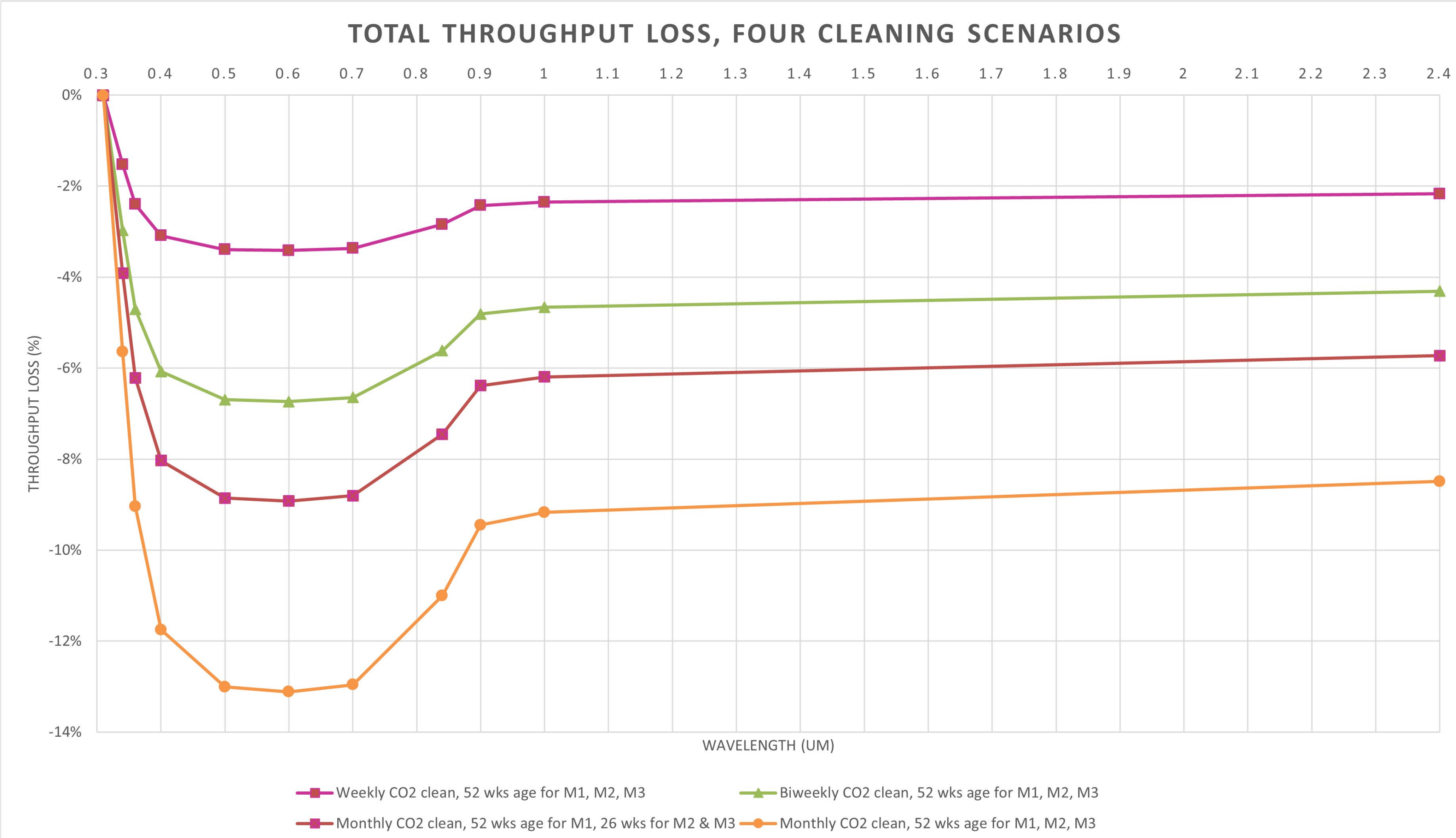

Figure 2-4 – Total telescope throughput loss (M1, M2 and M3 combined), for four different cleaning scenarios. Note that the green line for fortnightly CO2 cleaning is the baseline scenario for TMT.

Figure 2-3 above shows that below 1000nm, throughput is susceptible to faster degradation than higher wavelengths if cleaning is done less frequently. Science via instruments at these shorter wavelengths (such as WFOS) could be significantly affected without adequate cleaning. Additionally, the cleaning and recoating intervals have a large effect on overall telescope throughput.

Figure 2-4 is the difference between fresh coating total throughput and four different cleaning scenarios (i.e. the combined throughput loss of M1, M2 and M3) over the two year period assumed as the recoating cycle for all mirrors. The results for each scenario are:

1. Results in estimated ~1.5-3.4% total throughput loss (~2.35% above 1000nm)
2. Estimated ~3-6.7% total throughput loss (~4.6% above 1000nm)
3. Estimated ~3.9-8.9% total throughput loss (~6.2% above 1000nm)
4. Estimated ~5.6-13.1% total throughput loss (~9.1% above 1000nm)

To maintain adequate throughput at the baseline level, it is necessary to CO2 clean all mirrors every two weeks and wet wash or recoat M2 & M3 yearly, as per scenario 2. Alternatively, it would be possible to CO2 clean monthly all mirrors and maintain throughput at less than 3% loss per mirror by recoating or wet washing M2 and M3 every 26 weeks, as per scenario 3. It is clear that maintaining total telescope throughput will be difficult if M2 cannot be wet washed to restore performance in addition to regular CO2 cleaning.

3. APPENDIX

3.1 GEMINI 4-LAYER COATING REFLECTIVITY

The following plot of Gemini 4-Layer recipe coating against other coatings in development is sourced from Section 7.6 “Example Mirror Reflectance Curves” of RD6.

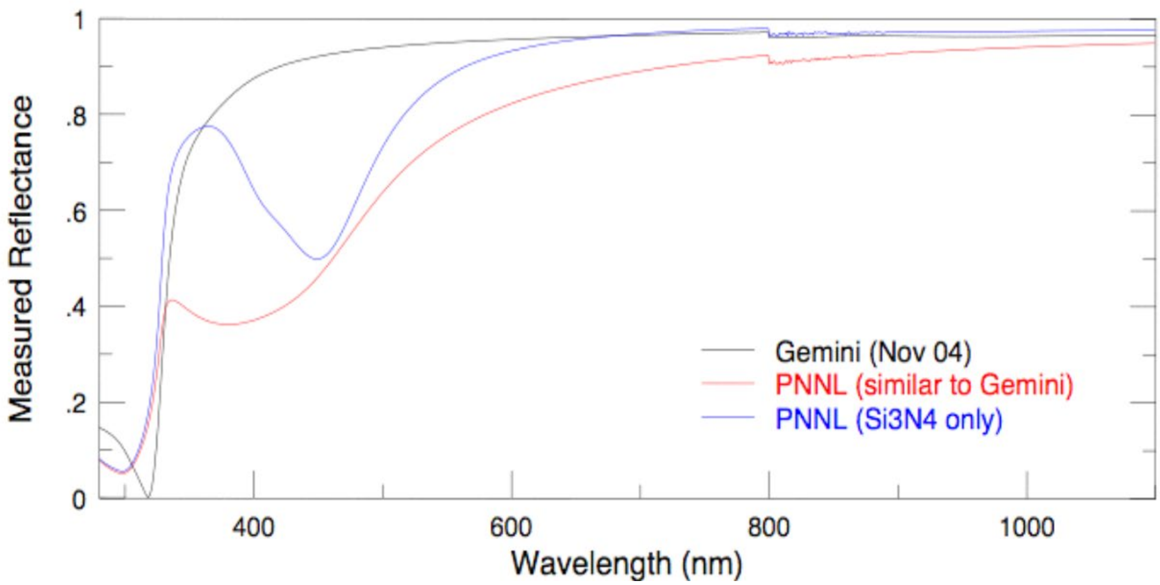

Figure 3-1 - Gemini coating plus other coatings in development. Dip in reflectivity other coatings is caused by surface Plasmon resonances.

Table 3-1 - Gemini 4-layer recipe fresh coating reflectivity - data for specific wavelengths

Wavelength (um) (Fresh coating)												
	0.31	0.34	0.36	0.4	0.5	0.6	0.7	0.84	0.9	1	2.4	28
R_GN2013	0.0287	0.5771	0.7370	0.8427	0.9300	0.9511	0.9619	0.9712	0.9731	0.9756	0.9910	no data
R_GS2010	0.0460	0.5753	0.7273	0.8647	0.9394	0.9571	0.9672	0.9752	0.9776	0.9801	0.9864	no data
R_GN2004	0.0412	0.6186	0.7733	0.8780	0.9409	0.9576	0.9664	0.9745	0.9759	0.9757	no data	no data
R_Average	0.0386	0.5903	0.7459	0.8618	0.9368	0.9553	0.9652	0.9736	0.9756	0.9771	0.9887	
R_stdev	0.008917	0.024488	0.024247	0.017852	0.005939	0.003609	0.002883	0.002128	0.00226	0.002532	0.00327	

3.2 GEMINI REFLECTIVITY LOSS PER YEAR, PERIOD 2008-2013

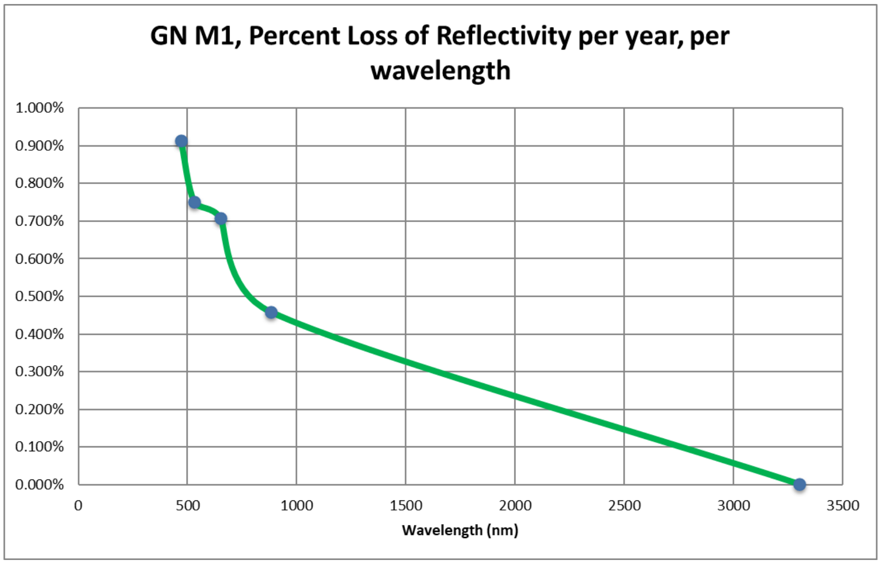

Figure 3-2 - Gemini North reflectivity loss per year, 2008-2013

3.3 REFLECTIVITY LOSS OVER TIME, MONTHLY

Data for reflectivity loss is normalized to yearly intervals, as shown in Section 2.1.2 Throughput Degradation Rates. To estimate month-on-month performance, these yearly values are divided evenly across all months. This therefore does not account for any seasonal variation in dust accumulation or degradation rate. Given that both the data and estimates are for time scales of greater than 1 year, this is acceptable.

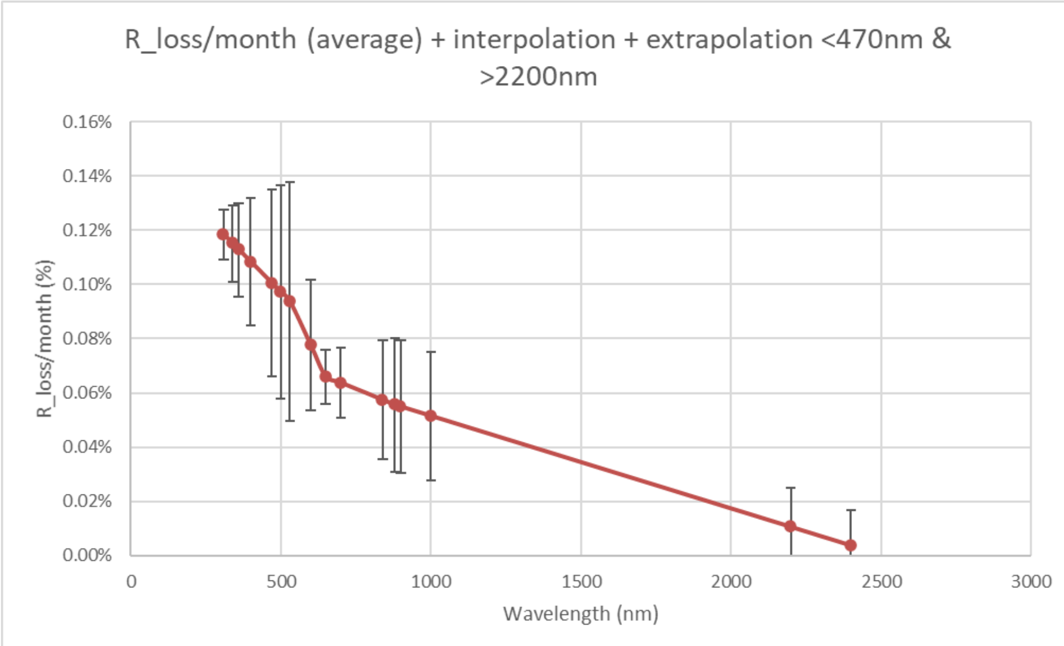

Figure 3-3 - Reflectivity loss per month, averaged, with inner linear interpolation and extrapolation for <470nm and >2200nm.

3.4 CLEANING GAIN, CTIO

The 36” CTIO telescope uses CO2 cleaning and wet washing on a regular basis to maintain reflectivity, and has compiled data on the effectiveness of the two methods. Cleaning effectiveness (gain) is effectively linear across the 400 – 700nm wavelengths shown (no other data available). This plot was sourced from RD3.

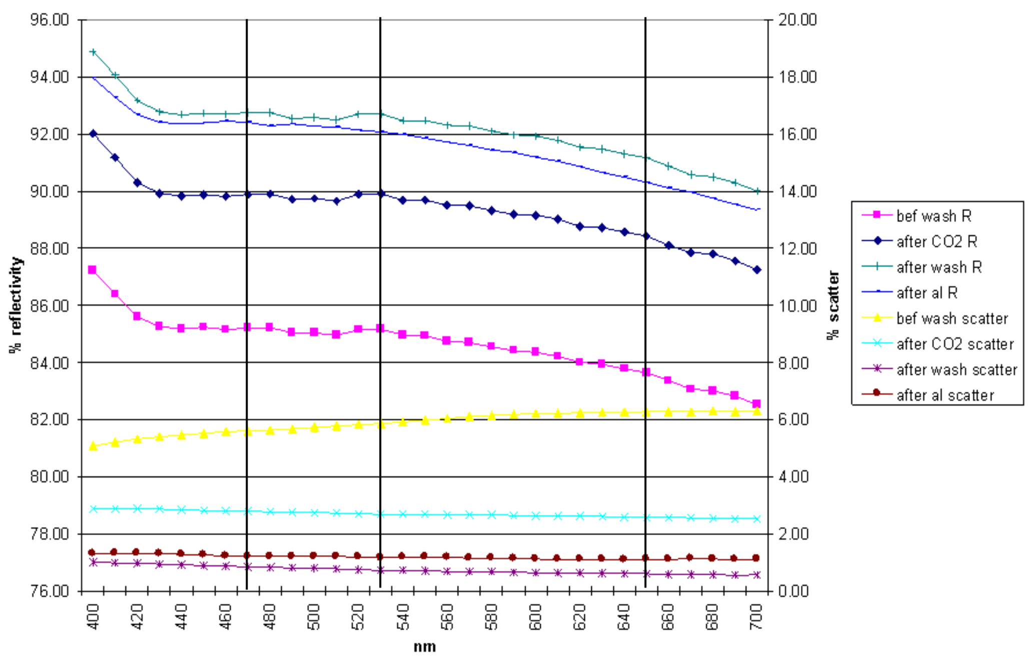

Figure 3-4 - CTIO mirror cleaning effectiveness