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CHEOPS THROUGHPUT ANALYSIS

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1 INTRODUCTION

This document is aimed to provide the results of the CHEOPS TEL throughput analysis, including EOL cases, on the basis of the available experimental results concerning the radiation effects on the optical substrates and coatings.

1.1 Scope

The present document is issued in the frame of the CHEOPS TEL/SSA subsystem to be provided from LEONARDO to ASI for the phase B/C/D project. The TEL/SSA subsystem is part of the instrument to be flown onboard the CHEOPS Mission that is envisaged as a partnership between Switzerland (Universities of Bern, Genève and the Swiss Space Center) and ESA's Science Program for the discovery of extra-solar planets.

The Italian contribution to the CHEOPS mission is funded by ASI with the contract N. 2014-032-I.0, CIG 5470246DCA, CUP F82F14000160005.

The commission in charge of the Italian industrial team, composed by LEONARDO (Italian Prime Contractor), TAS-I and Media Lario, mainly concerns the manufacturing of the PFM instrument parts denominated Telescope (TEL) and Back End Optics (BEO) and align and integrate these subsystems inside the Support Structure Assembly (SSA) developed by the Mission Prime, Universities of Bern (UBE), and provided by ASI to LEONARDO as furnished equipment (AFE).

The industrial activities are developed in strict collaboration with the other members of the CHEOPS Consortium having a role relevant for the TEL/SSA provision and mainly given by UBE for the system and structural aspects and INAF for the optical and alignment aspects.

1.2 Applicability

The present document is applicable to the CHEOPS TEL subsystem.

2 REFERENCE DOCUMENTS

2.1 Applicable Documents

Ref.	Identifier	Title
A1.		Istruzione Operativa "Preparazione e trasmissione dell'offerta all'ASI" – Doc. OP-IPC-2005-012
A2.		Capitolato Generale ASI, disponibile su http://www.asi.it/files/20070905110555cap_gen.pdf
A3.	OP-QTA-2012-003	Istruzione Operativa "Linee guida per il Tailoring delle norme ECSS"
A4.	OP-QTA-2012-004	"Tailoring per Space Engineering Software e Software Product Assurance"
A5.	OP-IPC-2005-010	Istruzione Operativa "Capitolato gestionale delle Richieste d'Offerta dell'ASI"
A6.	OP-IPC-2005-002	Istruzione Operativa "Requisiti per la preparazione della Work Breakdown Structure (WBS)"
A7.		Tailoring di Primo Livello delle Norme ECSS Serie M-Q-E - DC-QTA-2014-001, 10/01/2014
A8.	DC-QTA-2014-002 10/01/2014	PA Requirements
A9.	ECSS-S-ST-00-01C	ECSS Glossary
A10.	CHEOPS-UBE-MA-PL-001	PMP
A11.	CHEOPS-INAF-INST-PL-001	TEL Management Plan
A12.	CHEOPS-UBE-MA-PL-003	Risk Management Plan
A13.	CHEOPS-UBE-MA-SC-001	Master Schedule
A14.	CHEOPS-UBE-INST-CI-001	CHEOPS Instrument Configured Items List (CI)
A15.	CHEOPS-EST-INST-DRD-002	CHEOPS Instrument Documents Requirements Definition (DRD)
A16.	CHEOPS-EST-INST-DRD-001	CHEOPS Instrument Documents Requirements List (DRL)
A17.	CHEOPS-EST-MA-PR-001	CHEOPS Documentation Configuration and Management Procedure
A18.	CHEOPS-INAF-INST-PT-001	TEL Product Tree
A19.	CHEOPS-INAF-INST-WBS-001	TEL INAF WBS
A20.	CHEOPS-INAF-INST-LI-002	TEL Configuration Item Data List
A21.	CHEOPS-INAF-INST-LI-00	TEL Document Status List
A22.	CHEOPS-INAF-MA-SC-001	TEL Schedule
A23.	ECSS-Q-ST-10C	
A24.	ECSS-Q-ST-20C	
A25.	OP-QTA-2012-005	Istruzione Operativa "Norme per la redazione del Piano di Assicurazione del Prodotto (PA Plan)"
A26.	UNI EN ISO 9001:2008	"Sistemi di Gestione per la Qualità"
A27.	CHEOPS-UBE-INST-PL-003	Product Assurance Plan
A28.	CHEOPS-INAF-INST-PL-003	TEL Product Assurance Plan

Ref.	Identifier	Title
A29.	CHEOPS-EST-SCI-RS-001	Scientific Requirements Document
A30.	CHEOPS-EST-SYS-RS-001	System Requirements Document
A31.	CHEOPS-EST-INST-EID-001	EIDA
A32.	CHEOPS-UBE-INST-EID-001	EIDB
A33.	CHEOPS-UBE-INST-RP-003	Contamination Analysis Report
A34.	CHEOPS-UBE-INST-PL-004	Contamination Control Plan
A35.	CHEOPS-UBE-INST-WBS-001	CIS Work Breakdown Structure
A36.	CHEOPS-UBE-INST-PT-001	CIS Product Tree
A37.	CHEOPS-UBE-INST-RS-001	Instrument Requirements Specification
A38.	CHEOPS-EST-INST-RS-001	ECSS-Engineering Tailoring CHEOPS tailoring for ECSS Engineering standards
A39.	CHEOPS-UBE-INST-ICD-002	OTA Interface Control Document
A40.	CHEOPS-INAF-INST-RS-001	TEL subsystem requirements
A41.	CHEOPS-UBE-INST-RS-002	CHEOPS STRUCT sub-system RS
A42.	CHEOPS-INAF-INST-DD-001	CIS-TEL Optical Design
A43.	CHEOPS-UBE-INST-TN-002	PSF Merit Function
A44.	CHEOPS-INAF-INST-ADD-008	Zemax model of TEL OD
A45.	CHEOPS-UBE-INST-DD-002	STRUCT Sub-System Design Description
A46.	CHEOPS-UBE-INST-LI-005	STRUCT-TEL Deliverable Items List (DIL) - OTA Unit
A47.	CHEOPS-INAF-INST-PL-002	TEL AIV Plan
A48.	CHEOPS-INAF-INST-TN-005	Specifications for blanks of STM, DM and EQM-BEO Mirrors
A49.	CHEOPS-UBE-INST-TN-001	Sub-System Preliminary Mechanical Environments
A50.	CHEOPS-INAF-INST-LI-003	TEL IRS Flow down matrix
A51.	CHEOPS-INAF-INST-ICD-001	TEL Optical Interface Control Document
A52.	DC-EOS-2014-238 del 25/07/2014	ALLEGATO TECNICO GESTIONALE AL CONTRATTO ASI N. 2014-032-I.0 “CHEOPS – Attività industriali di fase B/C/D”

2.2 Referenced Documents

Ref.	Number	Title
R1.	ECSS-M-ST-60C	Cost and schedule management
R2.	CHEOPS-EST-SCI-PL-001	Science Management Plan
R3.		Multilateral Agreements (MLA, to be released)
R4.	CHEOPS-UBE-INST-PL-001	CHEOPS Instrument Management Plan
R5.	CHEOPS-UBE-MA-RS-001	Document Requirements
R6.	CHEOPS-EST-MA-PR-001	Document configuration 15May2013
R7.	CHEOPS-UBE-MA-LI-001	Document matrix
R8.	CHEOPS-UBE-INST-LI-001	LLIL and CIL

Ref.	Number	Title
R9.	CHEOPS-UBE-MA-LI-004	Risk register
R10.	CHEOPS-UBE-INST-PL-003	AIV and Test Plan CHEOPS Instrument
R11.	CHEOPS-INAF-INST-DD-002	Conceptual Design Description of mounts of TEL optical elements
R12.	CHEOPS-INAF-INST-RP-001	CIS-TEL Straylight Analysis
R13.	CHEOPS-CSL-BCA-TN-001	CHEOPS BCA FEM description
R14.	CHEOPS-UBE-INST-RS-006	STRUCT MGSE Specification
R15.	CHEOPS-UBE-INST-RP-002	CIS Instrument Budgets Report
R16.	CHEOPS-UBE-INST-PL-006	CIS AIV and Test Plan
R17.	CHEOPS-UBE-INST-DD-001	Instrument Design Report
R18.	Selex ES/Space/14/112	Offerta Tecnica di SELEX-ES in risposta alla RdO “Attività industriali di fase B/C/D del programma CHEOPS”
R19.	CHEOPS-SES-INST-SP-002 rev. 1	CHEOPS Optical Coating Specification
R20.	CHEOPS-EST-INST-TN-008 issue 1 rev. 0	CHEOPS Instrument Radiation Analysis
R21.	CHEOPS-SES-INST-RP-010 Rev. 0	CHEOPS TEL radiation effects on OHARA S-FPL51 and S-NBH5
R22.	RTI0890 Rev. 1	HR Qualification Report for CHEOPS-SES-INST-RS-002
R23.	RTI0889 Rev. 1	AR Qualification Report for CHEOPS-SES-INST-RS-002

3 DEFINITIONS & ACRONYMS

3.1 Definitions

Terms	Description
TEL	The subsystem made by the assembly of an Opto-Mechanical Tube (OMT), consisting of a mechanical structure (TTA) housing the primary (M1) and secondary (M2) mirrors, an Optical Bench Assembly (OBA), and Back-End Optics (BEO), consisting of a mechanical part (BEO Assembly) mounting the set of D1G, Diaphragm, M3G and D2G opto-mechanical subassemblies.
SSA	The subsystem made by the Support Tube Extension, the Main Bipod Assembly, and the Structure Tube. It is part of the STRUCT.TEL.
STRUCT.TEL	Collective name for the mechanical structures that are used for TEL assembly (TTA, OBA, BEO Assembly, and SSA) and are released by the UBE.
Optical Train	Collective name for M1G+M2G+D1G+M3G+D2G.

3.2 Acronyms

Acronym	Description
ABCL	As Built Configuration List
AD	Applicable Document
ADC	Analog to Digital Converter
ADCS	Attitude Determination and Control System
ADP	Acceptance Data package
ANT	Average of the NT
AR	Anti-Reflectance
BB	Breadboard
BCA	Baffle Cover Assembly
BEE	Back End Electronics
BEO	Back End Optics
BOLT	Begin Of Life Throughput
B-S	Beam-Splitter
CCD	Charge-Coupled Device
CDR	Critical Design Review
CFI	Customer Furnished Item
CHEOPS	Characterizing ExOPlanet Satellite
CIDL	Configuration Item Data List
CIL	Critical Items List
CIS	CHEOPS Instrument System, the instrument
CMC	CHEOPS Mission Consortium
CoC	Certificate of Conformance
COTS	Commercial-Off-the-Shelf

D1	BEO 1st doublet lens (the 1st in the optical path)
D1G	D1 Group=D1+D1 Mount
D2	BEO 2nd doublet lens (the 2nd in the optical path)
D2G	D2 Group=D2+D2 Mount
DCL	Declared Components List
DIL	Deliverable Items List
DM	Demonstration Model
DML	Declared Material List
DMPL	Declared Mechanical Part list
DPL	Declared Process List
DRB	Delivery Review Board
DRL	Document Requirements List
EAF	EOL Attenuation Factor
EEE	Electrical, Electronic and Electromechanical
EFL	Effective Focal Length
EGSE	Electrical Ground Support Equipment
EICD	Electrical Interface Control Document
EM	Electrical Model
EMC	Electromagnetic Compatibility
EOLT	End Of Life Throughput
EQM	Engineering Qualification Model
ESA	European Space Agency
ESD	Electrostatic Discharge
ETM	Electrical Test Model
F/W or FW	Firmware
FM	Flight Model
FMECA	Failure Modes, Effects and Criticality Analysis
FOV	Field of View
FoV	Field of View
FPA	Focal Plate Assembly
FPM	Focal Plane Module
FS	Flight Spare model
H/WorHW	Hardware
HK	Housekeeping
HSDP	High Speed Data Processor
HV	High Voltage
HR	High Reflectance

I/F	Interface
ICD	Interface Control Document
IIC	Italian Industrial Contractor
INAF	Istituto Nazionale AstroFisica
IRLST	Informative Reference Local Solar Time
IRS	Instrument Requirement Specification
KIP	Key Inspection Point
KoM	Kick-off Meeting
LLI	Long Lead Item
LV	Low Voltage
M1	TEL Primary Mirror
M1G	M1 Group=M1+M1 Mount
M2	TEL Secondary Mirror
M2G	M2 Group=M2+M2 Mount
MGSE	Mechanical ground support equipment
MICD	Mechanical Interface Control Document
MIP	Mandatory Inspection Points
MLI	Multi Layer Insulation
MOC	Mission Operations Center
MRR	Manufacturing Readiness Review
NCR	Non-Conformance Report
NR	Normative Reference
NT	Normalised Transmission
OACT	Osservatorio Astrofisico di Catania
OBA	Optical Bench Assembly
OGSE	Optical ground support equipment
OMT	Opto-Mechanical Tube
OTA	Optical and Telescope Assembly
PA	Product Assurance
PCB	Printed Circuit Board
PDR	Preliminary Design Review
PFM	Proto Flight Model
PI	Principal Investigator
PRR	Preliminary Requirements Review
QA	Quality Assurance
QM	Qualification Model
RD	Reference Document

REI	Requirement Equivalent Instrument
RFD	Request for Deviation
RFW	Request for Waiver
RID	Review Item discrepancy
RMS	Root Mean Square
S/C	Spacecraft
S/WorSW	Software
SAA	South Atlantic Anomaly
SFR	Square F-Number Ratio
SoW	Statement of Work
SSA	Support Structure Assembly
STM	Structural and Thermal Model
TBC	To Be Confirmed
TBD	To Be Defined
TEL	Telescope (CIS-601)
TICD	Thermal Interface Control Document
TID	Total Ionising Dose
TNID	Total Non-Ionising Dose
TRD	Total Radiation Dose (TID+TNID)
TRL	Technology Readiness Level
TRR	Test Readiness Review
TVM	Test and Verification Model
UBE	University of Bern
WBS	Work Breakdown Structure
WPD	Work Package Description

4 ANALYSIS INPUTS

The present analysis has been realized assuming the optical performance, in terms of transmittance and reflectance, provided by the experimental measurements on the substrates and coatings used for the CHEOPS TEL. The experimental results are reported in the documents summarized in Table 1:

Optical Component		Substrate	Coating
M1		Zerodur	HR according to [R22]
M2		Zerodur	HR according to [R22]
M3		Zerodur	HR according to [R22]
L1-COLL D1	D1	Ohara S-FPL51 according to [R21]	AR according to [R23]
L2-COLL D1	D1	Ohara S-NBH5 according to [R21]	AR according to [R23]
L1-RELAY D2	D2	Ohara S-FPL51 according to [R21]	AR according to [R23]
L2-RELAY D2	D2	Ohara S-NBH5 according to [R21]	AR according to [R23]

Table 1 – CHEOPS applicability matrix.

For the EOL calculation, the analysis has been carried out taking into account the degradation of the optical performance of each element of the CHEOPS optical chain, due to the expected radiation environment as reported in [R20].

According to [R20], the expected ionising (γ-rays) and non-ionising (proton fluence) radiation levels on the TEL optical elements are summarized in Table 2 and in Table 3 respectively.

Target	Average Dose [krad (Si)]	Min Dose [krad(Si)]	Max Dose [krad(Si)]
Primary mirror	61.53	52.66	70.89
Secondary mirror	1.52	1.39	1.64
Folding mirror	1.82	1.64	2.02
Doublet 1, front element	1.49	0.79	2.69
Doublet 1, rear element	1.38	0.84	1.86
Doublet 2, rear element	1.62	1.44	1.78

Table 2 - Ionising radiation doses for targets in optical system.

Target	Average Dose [#/cm^2]	Min Dose [#/cm^2]	Max Dose [#/cm^2]
Primary mirror	1.23E+10	1.11E+10	1.33E+10
Secondary mirror	4.84E+09	4.41E+09	5.21E+09
Folding mirror	5.44E+09	5.09E+09	5.79E+09
Doublet 1, front element	3.04E+09	2.65E+09	3.80E+09
Doublet 1, rear element	4.16E+09	2.80E+09	4.97E+09
Doublet 2, rear element	4.57E+09	4.43E+09	4.64E+09

Table 3 - Non-Ionising equivalent 10 MeV proton fluence for targets in optical system.

In Figure 1 the ionising dose profile falling on the first lens of the first TEL doublet (D1), as specified in [R20], is shown. The profile in Figure 1 is due to the hardware configuration shown in Figure 2.

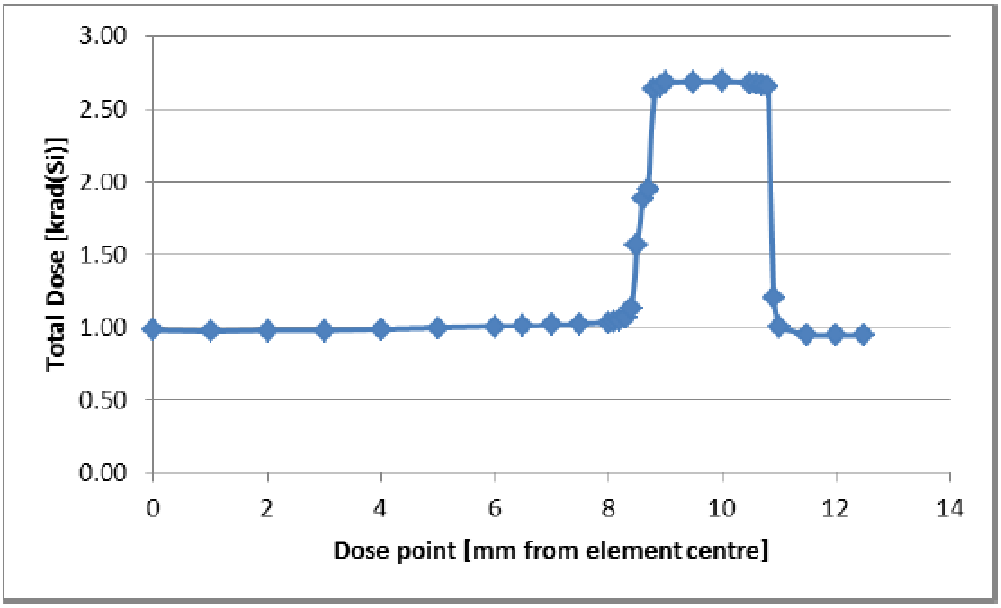

Figure 1: Ionising dose profile across front element of Doublet-1.

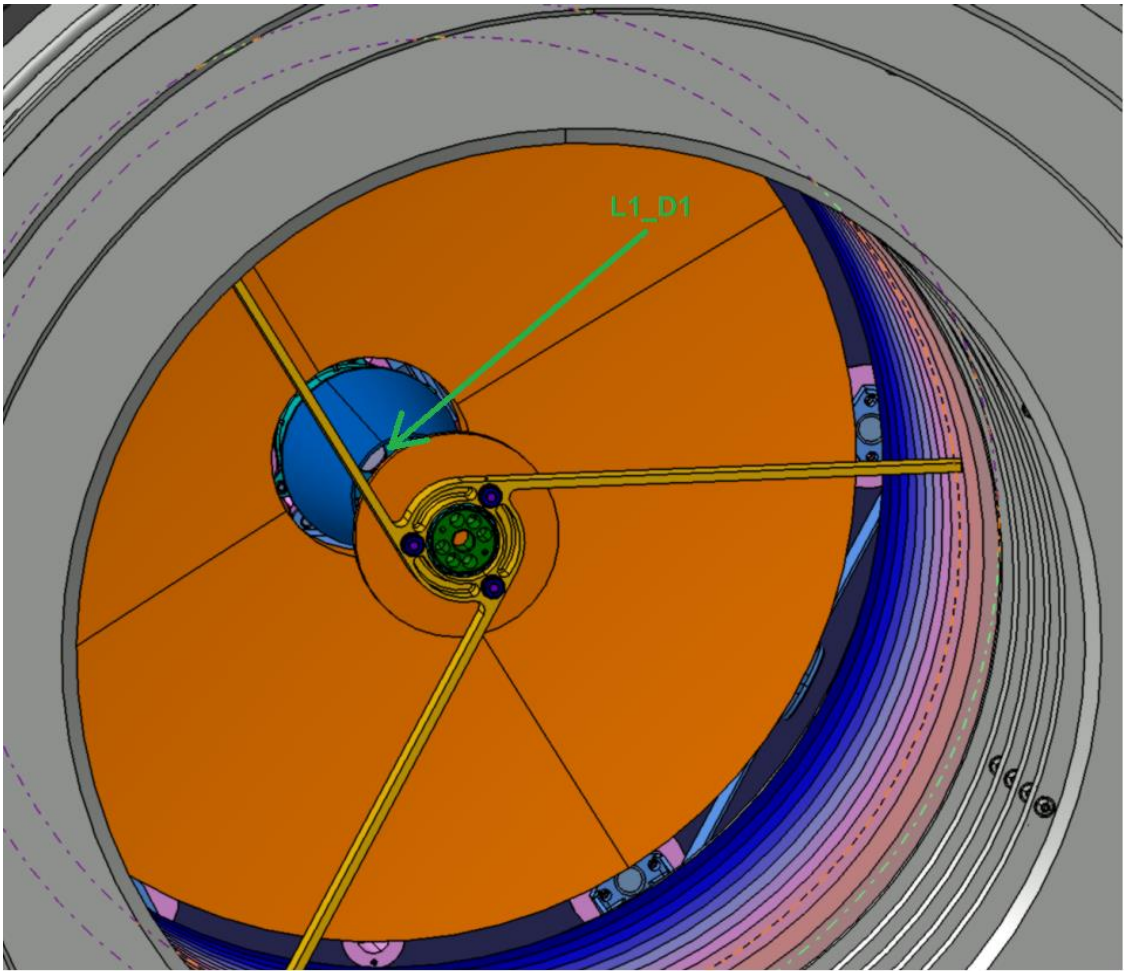

Figure 2: Portion of L1 not hidden from baffles.

5 THROUGHPUT ANALYSIS

The throughput analysis of the CHEOPS optical chain has been carried out with the help of the simulation software Zemax® for an unpolarised source placed on-axis and in the marginal field, taking into account the presence of the spiders and the M1 obstruction. For each field has been achieved the average transmittance of the overall optical system in the spectral range (400–1100) nm for BOL and EOL AVERAGE TRD x2 dose, assuming for each optical element the average ionising and non ionising irradiation dose reported in Table 2 and 3 respectively. The transmittance values obtained by simulations have been rescaled in order to taking into account the ratio between the solid angles subtended by an entrance pupil of 320 mm in diameter and 300 mm respectively, according to the requirement Ref. L3-TEL-FCT-6 disclosed in [A40].

5.1 BOL Analysis

The optical performance of the coating used to compute the BOL analysis are shown in Figure 3 and Figure 4 (concerning the transmittance at AOI=0° (blue curve) and the corresponding requirement (red curve) of the AR coating for the two Ohara substrates) and in Figure 5 (concerning the reflectance at AOI=0° (blue curve) and the corresponding requirement (red curve) of the HR coating on Zerodur). These performances have been measured on samples before environment tests and radiation exposures.

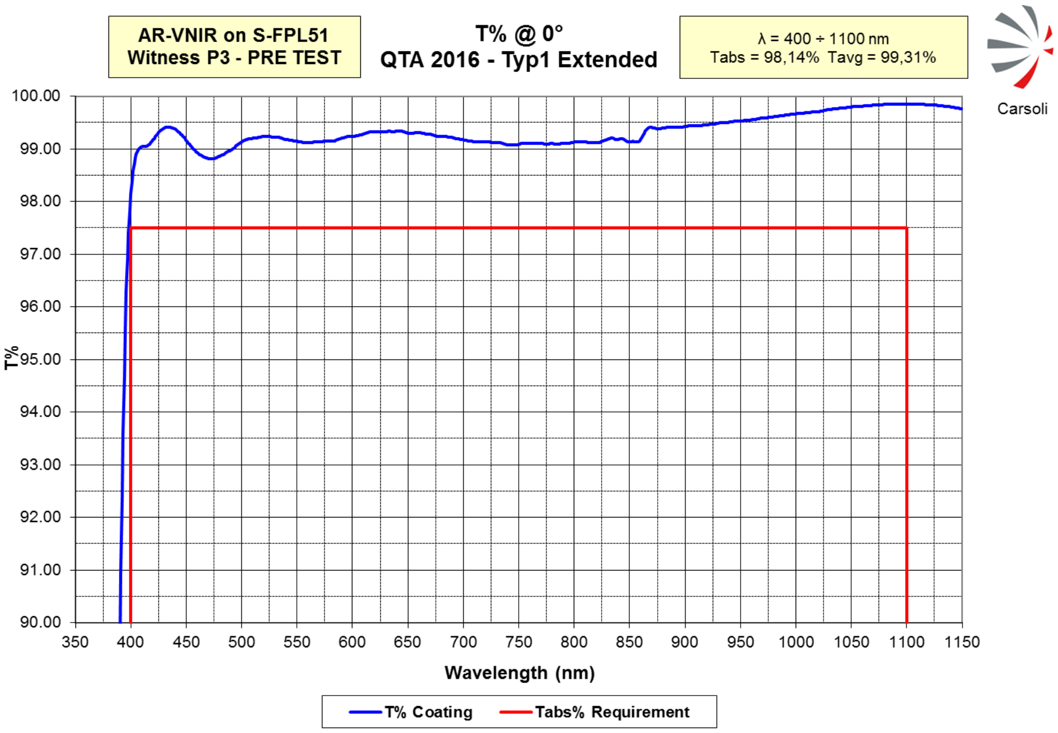

Figure 3: AR coating transmittance on S-FPL51 substrate at AOI=0°. The color code of the curves is described in the legend.

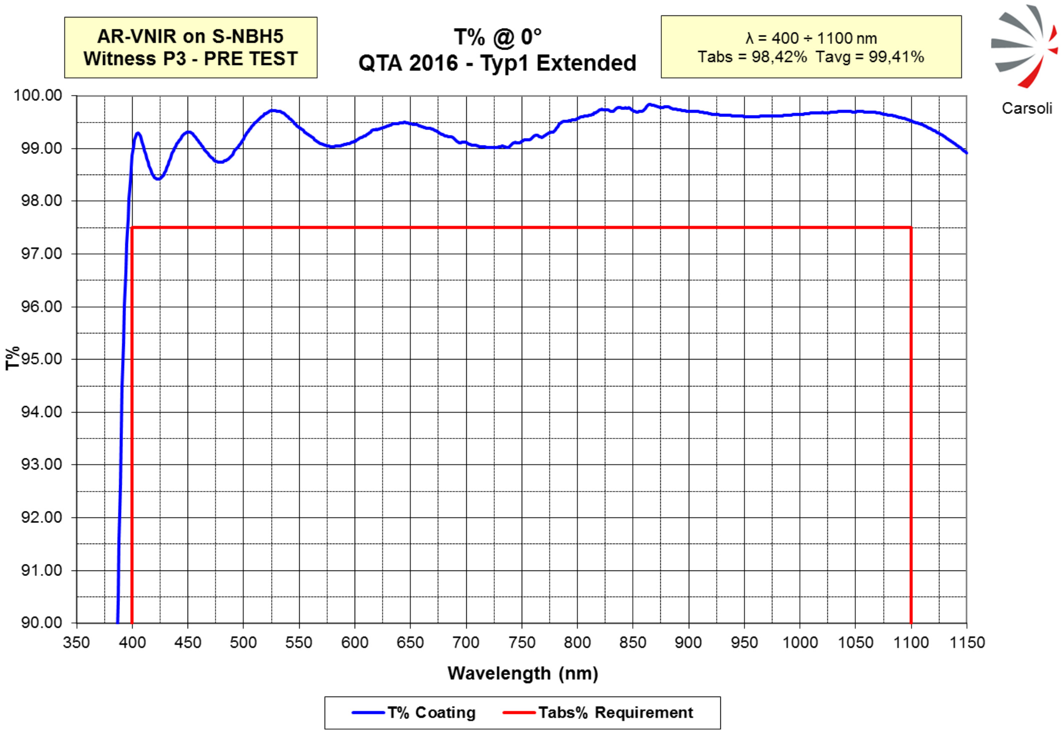

Figure 4: AR coating transmittance on S-NBH5 substrate at AOI=0°. The color code of the curves is described in the legend.

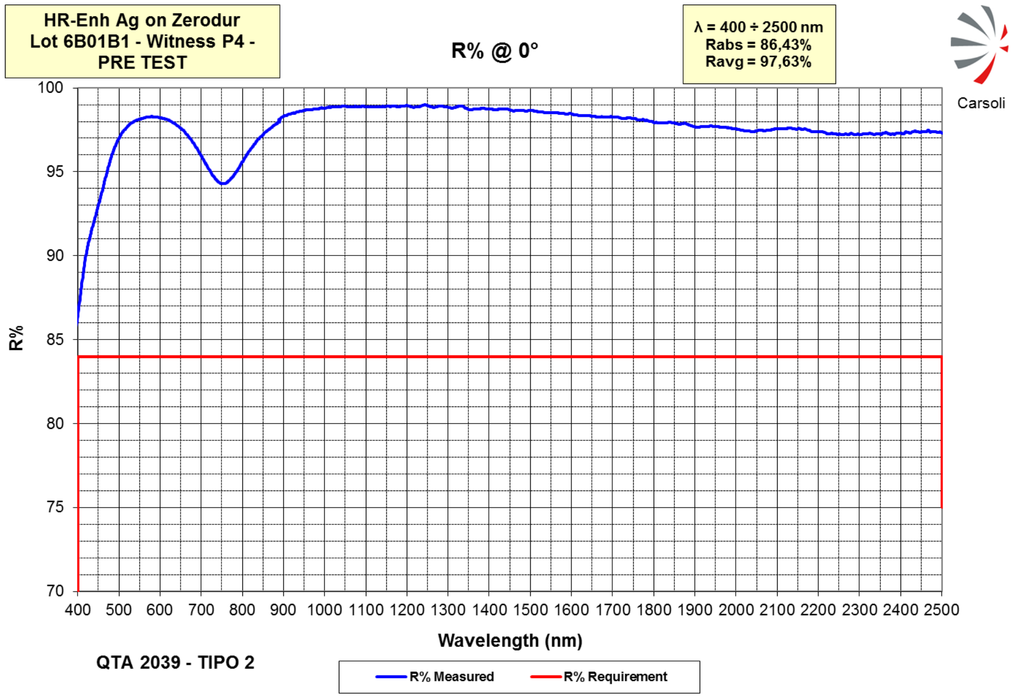

Figure 5: HR coating reflectance on Zerodur at AOI=0°. The color code of the curves is described in the legend.

Considering all the TEL optical surfaces, including spiders and M1 obscuration, the resulting BOL throughput result is reported in Figure 6 . The corresponding average value within spectral range is 90.5%.

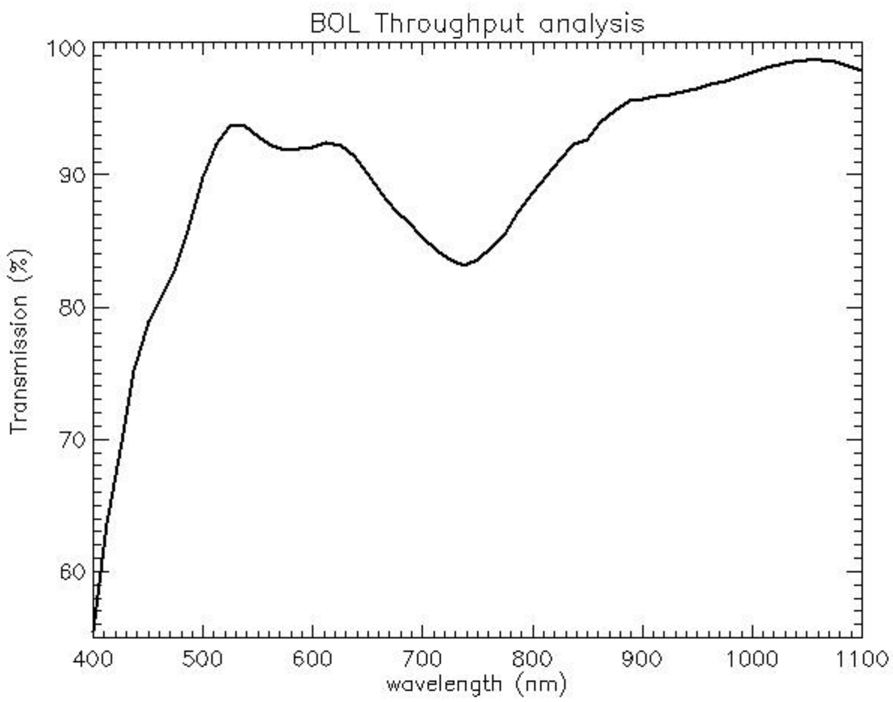

Figure 6: BOL throughput analysis result.

5.2 EOL Analysis

Analogously to the BOL analysis, the EOL analysis has been computed by employing the experimental data concerning the spectral performance of the Ohara substrates and coatings after different cumulative irradiation levels of γ-rays and protons, as reported in [R21], [R22] and [R23]. The spectral performance assigned to each optical element (mirrors, lenses and respective coatings) of the CHEOPS optical chain, have been opportunely rescaled starting from the available EOL experimental data, in order to take into account the different environment radiation levels falling on optical targets, as disclosed in [R20],

5.2.1 Ohara substrate degradation due to gamma and proton irradiation

The degradation of Ohara substrates S-FPL51 and S-NBH5 due to gamma irradiation has been measured by test on uncoated samples as reported in [R21]. In Figure 7 the percentage variation of the internal transmittance of the two kinds of Ohara glasses due to 1mm of bulk material, after 3krad gamma exposure, is shown.

It is important to point out that the first lens of each doublet is made of S-FPL51, and it is thicker than the second one, which is realized in S-NBH5. Since the internal transmittance of the S-FPL51 is more affected by the radiations in the range 400 to 600 nm, the S-FPL51 lenses contribute more than the S-NBH5 lenses to the radiation damping transmittance due to their greater thickness and intrinsic properties.

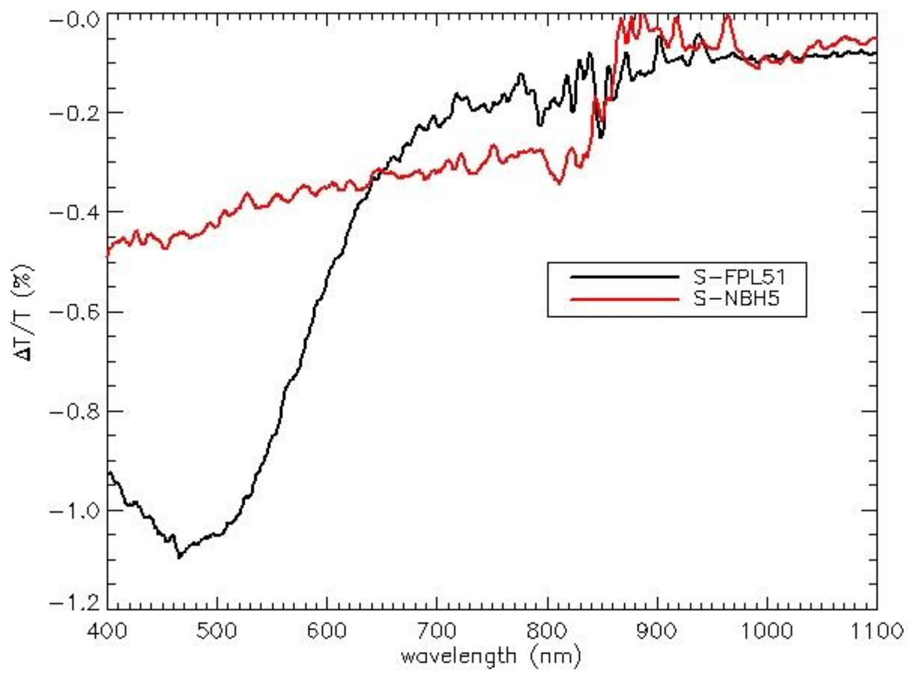

Figure 7: Percentage degradation of the internal transmittance for the Ohara substrates due to 1mm of material after 3krad gamma rays exposure (no coating is includes). The color code of the curves is described in the legend.

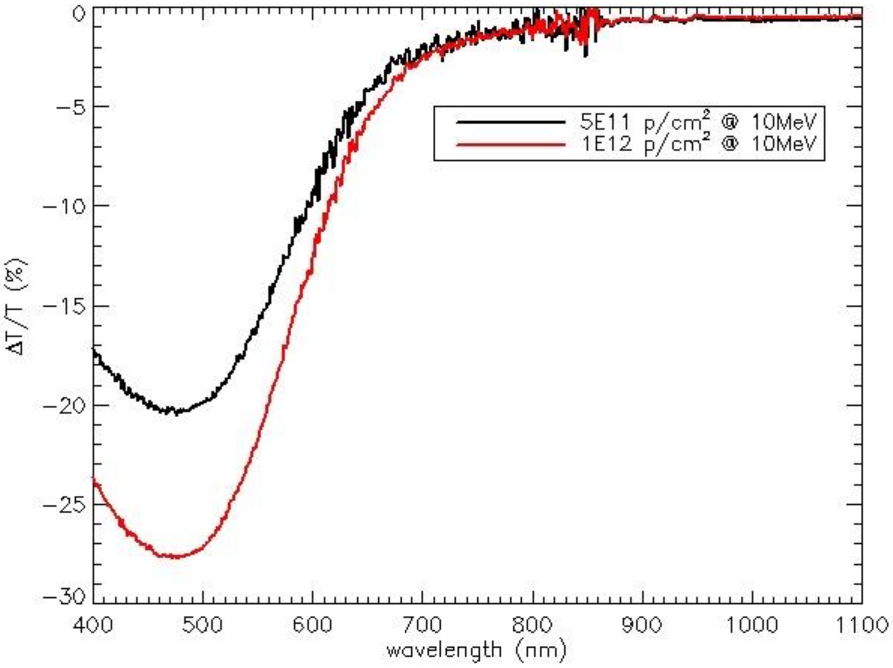

Figure 8: Percentage degradation of the internal transmittance for the S-FPL51 substrate (2 mm thick) after two different levels of proton exposures. The color code of the curves is described in the legend.

The effects of the proton irradiation on the Ohara substrates have been experimentally tested for two different values of proton fluence, in particular for 5·E11 p/cm² (half dose) and 1·E12 p/cm² (full dose) at 10MeV, as disclosed in [R21]. In Figures 8 and 9 the percentage variations of the internal transmittance for the S-FPL51 (2 mm thick) and S-NBH5 (3 mm thick) substrate, due to the different doses of proton fluence, are shown respectively.

The results of the experimental tests have underlined as the effects of the proton exposure result to be stronger, in terms of internal transmittance degradation, respects to the γ-rays irradiation. Moreover, analogously to the case of the γ radiations, it is important to point out the fact that the effects of the proton exposure are more evident for the S-FPL51 Ohara glass than the S-NBH5, in particular in the spectral range between 400 nm and 650 nm. However the maximum level of environment proton fluence is about two/three orders of magnitude lower than the tested experimental levels. For this reason, rescaling the experimental data to the values reported in Table 2, the amount of the effects of the protons irradiation on the internal transmittance of the two kinds of glasses is almost negligible, however its effect has been taken into account in the analysis.

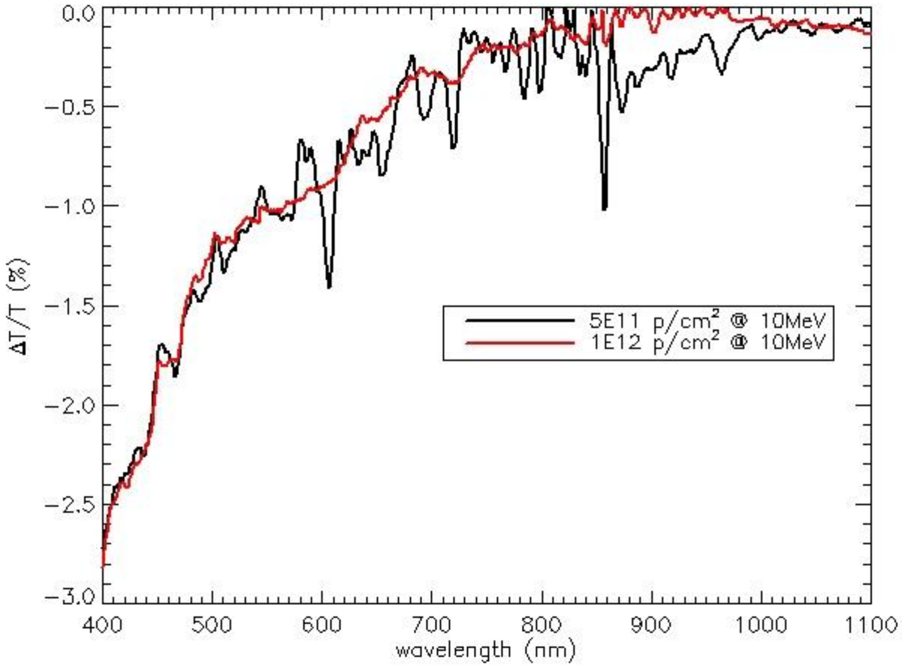

Figure 9: Percentage degradation of the internal transmittance for the S-NBH5 substrate (3mm thick) after two different levels of proton exposures. The color code of the curves is described in the legend.

5.2.2 HR mirror coating degradation

The experimental results on the effects on the HR coating after a cumulative exposure of 142 krad(Si) and 1E12 p/cm² @ 10MeV have underlined the presence of a small degradation of the coating optical performance, states in terms of percentage variation between the irradiated and no-irradiated case, less than 1.3%, especially in the spectral range (600-900)nm, as shown in Figure10.

Recalling the fact that, according to Table 2, the maximum environment level of proton fluence is about 3 order of magnitude smaller than the experimental level, the rescaled data for M1 have shown a degradation of the coating optical performance, of about 0.7% at 142 krad(Si) and 0.35% at 71 krad(Si), as average value on the whole spectral range.

Concerning the coating performance for M2 and M3, whose maximum radiation dose is of about 4krad(Si), the EOL degradation of the HR coating optical performance has been found to be less than 0.05%.

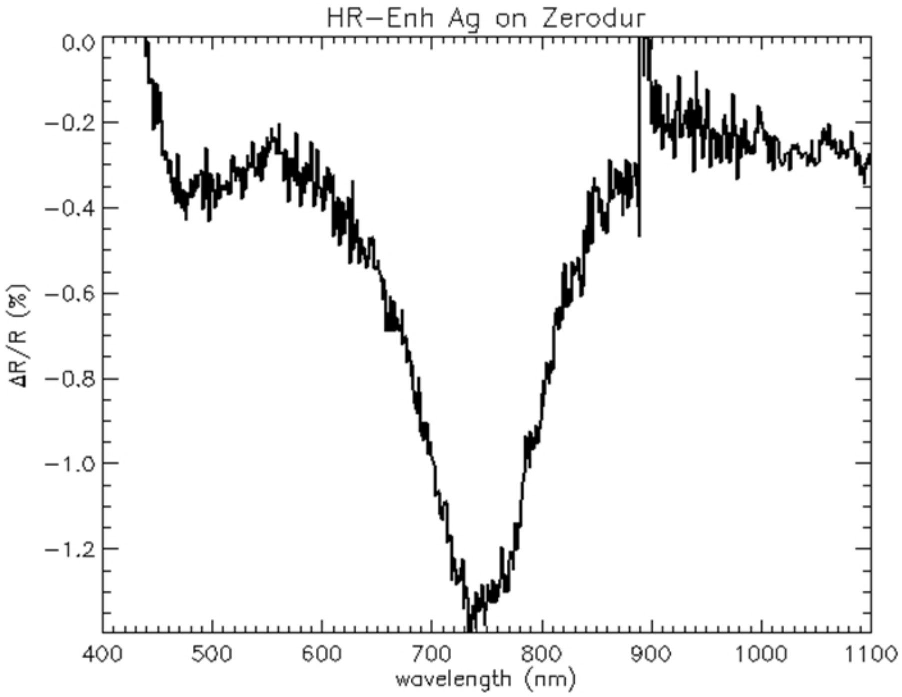

Figure 10: Percentage variation of the HR-coating reflectance on Zerodur at AOI=0° after a cumulative exposure of 142 krad(Si) and 1E12 p/cm² @ 10MeV.

5.2.3 Ohara lenses AR coating degradation

The optical performance of the AR coating have been experimentally tested at 3krad(Si) + 5E9 p/cm² @ 10MeV (half dose) and at 6 krad(Si) + 1·E12 p/cm² @ 10MeV (full dose), on the two different Ohara substrates, as reported in [R23]. The experimental data have underlined a percentage degradation of the coating performance less than 1% for the maximum radiation dose respect to the not irradiated coating, as shown in Figure 11.

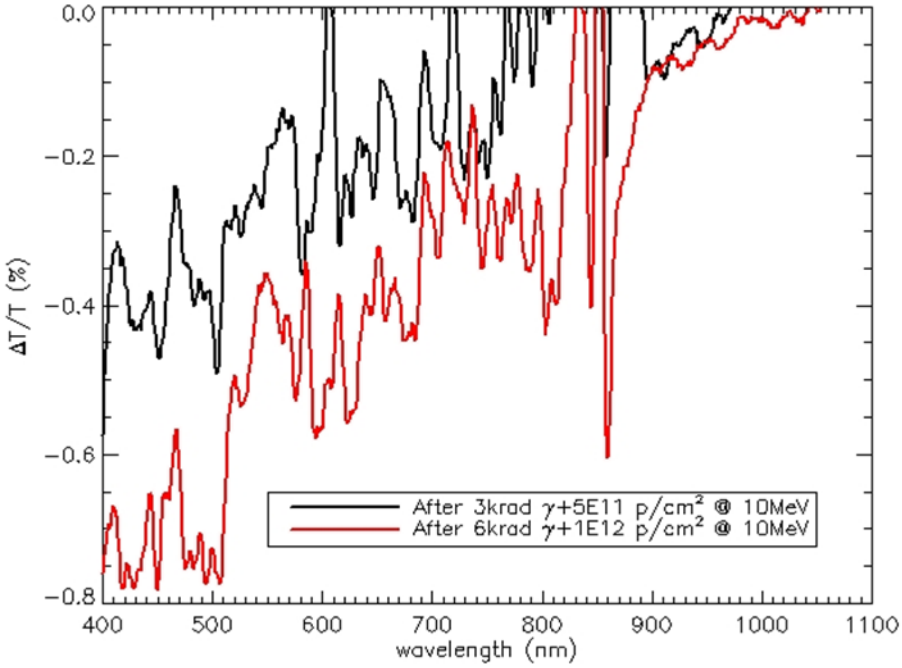

Figure 11: Percentage variation of the AR-coating transmittance at AOI=0° after two different values of TDR doses. The color code of the curves is described in the legend.

5.3 EOL throughput results

The average throughput within the CHEOPS spectral range has been computed for the on-axis and marginal field of view assuming, for each system optical element, the respective EOL optical performance (in terms of transmittance and reflectance) rescaled from the experimental results according to their environment AVERAGE TRD x2 radiation exposure doses. This analysis has been computed assuming an uniform irradiation profile for D1 element. In Figure 12, the result of the EOL throughput analysis, for the on-axis field, is shown.

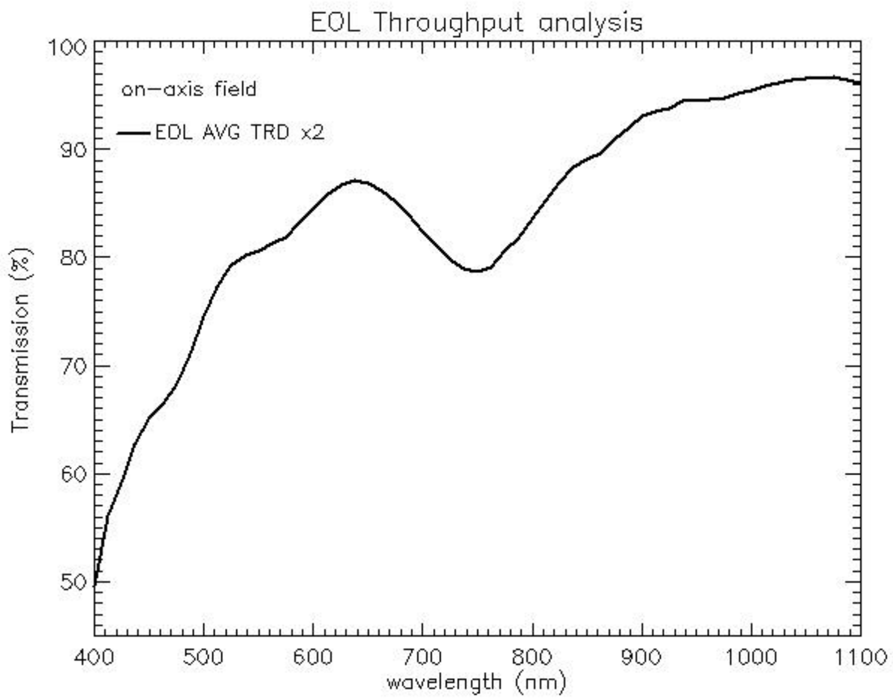

Figure 12: EOL AVERAGE TRD x2 dose throughput result for the on-axis field.

6 CONCLUSIONS

To conclude, with the employment of the available experimental data on the optical performance of the two Ohara glasses and coatings before and after the irradiation tests, have allow us to perform a throughput analysis that will reproduce, as much as possible, the performance of the CHEOPS optical system during the flight.

The experimental data have underlined that the worst offenders to throughput degradation are the materials of the four lenses in particular on S-FPL51 that is more degradable on 400-600 nm. Nevertheless, both materials confirm their moderate radiation resistance according to the papers in literature.

The results of the throughput analysis are summarized in Table 4 and in Figure 8, where is reported the average value between the on-axis and the marginal field transmittance result.

The 85% requirement of average throughput within the whole spectral range (Ref. L3-TEL-FCT-6) results to be satisfied for the BOL analysis, while the slight noncompliance for the EOL AVERAGE TDR x2 dose, is assumed to be acceptable due to the fact that we have considered a very conservative approach for the analysis, given by the application of the x2 safety factor to the EOL TRD, which is the common margin usually applied in the radiation analyses.

Radiation Dose	Transmittance (%)
BOL	90.5
EOL AVG TRD x2	84.1

Table 4 - Summary results of the throughput analysis.

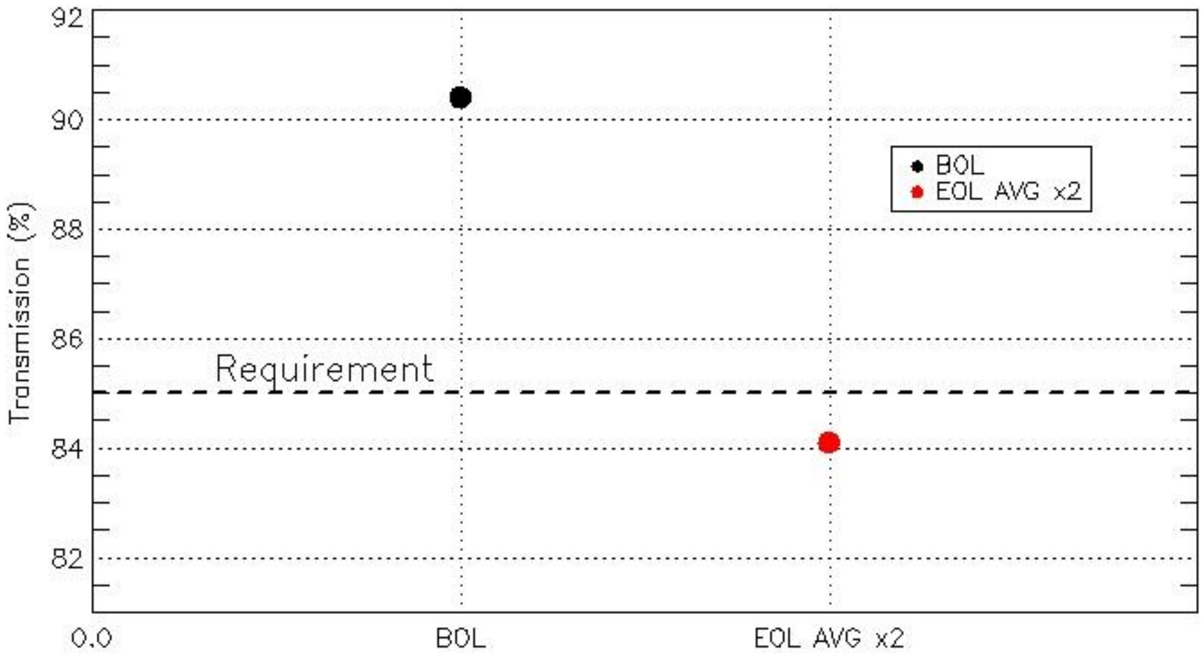

Figure 13: Throughput analysis summary results. The color code is described in the legend. Dashed line represents the 85% requirement for the average optical transmittance on the entire spectral range (400 -1100) nm.