estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

DOCUMENT

ATHENA - Mission Budgets Document

APPROVAL

Title ATHENA – Mission Budgets Document	
Issue 2	**Revision** 9
Author	**Date** 18/03/2020
Approved by	**Date**

CHANGE LOG

Reason for change	Issue	Revision	Date
Initial issue.	1	0	12/06/2014
Update to include non-x-ray particle background, absolute time accuracy and pointing requirements, and also general update.	1	1	20/08/2014
Included background update, and also placeholders for calibration of effective area. General update throughout.	1	2	26/02/2015
Update for industrial KO, on basis of: • Mission Operational Availability increase to 85% • Introduced placeholder for PSF HEW • Corrected small errors throughout	1	3	07/07/2015
Update #2 version – minor corrections, added FoV and effective area loss, SC op. av. Down to 90%	1	4	06/10/2015
Post MCR update	2	0	10/06/2016
Post document numbering system update	2	1	07/09/2017
Pre Prime Phase A CR update	2	2	18/10/2017
Post SR#1 update	2	3	05/03/2018
Post PhAx PM#1 update	2	4	30/04/2018
Pre Phase A2 Update	2	5	13/11/2018
Pre MFR	2	6	01/08/2019
B1 start	2	8	16/03/2020
B1 start corrected	2	9	18/03/2020

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CHANGE RECORD

Issue 2	Revision 0		
Reason for change	**Date**	**Pages**	**Paragraph(s)**
Updated the document reference number and the reference numbers of the affected ADs and RDs	07/09/2017		
Reason for change issue 2.0	**Date**	**Pages**	**Paragraph(s)**
MCR Update: Added PSF placeholder (overall PSF including pixel sampling – for completion by the ASST) Re-wrote Effective Area and Grasp section to remove baseline (small mirror) case and make clear that all effects are now under Prime responsibility (Mirror Area inc. internal effects, Mirror misalignment ref. LoS, LoS error, contamination) with examples only. Tightened AKE requirement (ASST justification received). Replaced RPE with RKE in pointing section, and relevance to HKE budget. Updated dV budget on the basis of MCR-consolidated budget, fixed noise value and including margins. Removed LV performance section – all information on LV, inc. performance, in the LS IRD.			
Issue 2.2: Returned the SC to the smaller 15-row mirror specification Improved the requirement break-down for A_eff (removed ‘target’ from the specification, now just on-axis) Net Observing Time breakdown included TBDs (no MOP available for new 4 year mission). Removed Effective Area calibration – will be handled by separate calibration plan and requirements – see Product Tree update.	Throughout		
Issue 2.3: Included de-focus in PSF HEW chapter. X-IFU 7’’ APE included (but justification still missing). Decomposition #GRB →ToO capability now unclear, maintained the previous 67% derivation. Consolidated background requirements chapter, but still preliminary (problems remain which are being looked at with ASST).	05/03/2018		

Updated NoP duration chapter to conform to new Mock Observation List. Introduced 3 WFI dwell-points description. Updated A_eff requirements to specify at target, and to correspond to CORE design point (15-rows) with SiC coating. Updated dV budget after redefinition with ESOC. Added system mass margin requirement for Phase A. Added A_eff loss during NoP.			
Issue 2.4 Inserted additional requirement on 50ks observation for ToO in the flow-down diagram for GRB-ToOs (consistent with the introduced requirement in the SRD). Updated the discussion about vignetting on the telescope to introduce <MA APE> (MA_optical_axis/target APE), as a replacement for the <LoS/target APE & MA_optical_axis/LoS APE>. Corrected a typo in grasp flow-down diagram. Cleaned up flow-down diagrams for background requirements, so that they are consistent with the requirements in the SRD. FL 25 mm offset for de-focused observations.			
Issue 2.5 Corrected SGS improvement factor for Wide-field astrometry from 3→4.5. Cleaned up background requirement flow-down (but still placeholders pending AREMBES outcome). Corrected 6→7 keV in A_eff requirements. Included preliminary justification for 7” APE from X-IFU SPA.			
Issue 2.6 Updated pointing chapter for latest information from PLs, and expanded definition per focal plane & dwell point. Updated A_eff requirements decomposition and explicitly declared shortfall w.r.t.a SciRD v2.4.			
Issue 2.8 Added interstitial blocking requirement on SC for x-ray background. Updated A_eff breakdown for new reference telescope design v2.6. Added other energies (Primes to still work just at 1 and 7 keV). Removed sys. Margin burn down chapter – not needed anymore.	16/03/2020		
Issue 2.9.			

Updated A_eff breakdown to include X-IFU 10 keV QE (was TBD), and QEs to 1 decimal place (WFI QE @ 0.2 keV is actually 5.8%. Corrected statements in §7.2.3.2 & §7.3 to clarify that Telescope Reference Document NO LONGER includes 10% margin.			

Table of contents:

1 INTRODUCTION & SCOPE

This document is the repository for the Mission-level performance breakdown and budgets, and is an instantiation of the Technical Budget standard DRD (Annex I of [AD01]), as part of the Mission DDF (DDF_1.0).

Regarding the flow-down of quantified requirements from the SciRD [RD01] and ConOps [RD07], via the MRD [RD02] to one of the tier-1 Product Tree [RD03] items, there are two cases:

1. A requirement is flown directly down to, and accordingly is the responsibility of, a single tier-1 product without decomposition/translation; in this case, the top-level budget for this requirement is the responsibility of the tier-1 product supplier, and will appear in the budget document associated with that product.
2. A requirement translation to one or more tier-1 products, or a requirement decomposition among two or more tier-1 products, is necessary; in this case, the top-level budget is the responsibility of the ESA PO, and is maintained in this document.

This document deals with the second case, and presents the budgets and models controlling the decomposition and/or translation of MRD requirements into engineering requirements allocated to tier-1 products in their respective specifications.

Note: Requirement decompositions are shown; goal decompositions follow the same approach.

1.1 Decomposed Mission Requirements

This document also currently contains two decompositions from the SciRD to the MRD which are the responsibility of the ASST:

- Net observing times
- GRB trigger efficiency

The following MRD/ConOps requirements are decomposed to tier-1 product specifications in this document:

- PSF HEW
- Operational availability
- Mission Reliability
- Effective Area & Grasp
- Effective Area loss during the NoP
- Field of View
- ToO reaction time
- Science telemetry latency
- Absolute time accuracy

- Background
- Astrometry and SC (telescope) pointing
- Delta V (station-keeping).

Furthermore, the mass-margin burn-down in assessment phase is justified.

Note: The decompositions are depicted graphically using colour coded box diagrams. Where appropriate, and for information only, the derived requirements used in the CDF study for the SC are presented as boxes with dashed-lines.

1.2 Applicable Documents

[AD01] Space engineering: System engineering general requirements, ECSS-E-ST-10C, Issue 3.0, 06/03/2009.

[AD02] Space Product Assurance: Availability analysis, ECSS-Q-ST-30-09C, Issue 2.0, 31/07/2008.

1.3 Reference Documents

[RD01] ATHENA - Science Requirements Document (SciRD)

[RD02] ATHENA - Mission Requirements Document (MRD)

[RD03] ATHENA - Product Tree, ESA-ATHENA-ESTEC-MAN-PT-0001

[RD04] ATHENA+: ATHENA+ Response Files, ECAP-ATHENA+-20130325, 25/03/2013.

[RD05] IXO baseline design report, IXO-TASF-RP-004, Issue 4.0, 30/07/2010.

[RD06] Space Debris Mitigation for Agency Projects. ESA/ADMIN/IPOL (2008), 1st April 2008, Annex 1 and 2.

[RD07] ATHENA – Concept of Operations, ESA-ATHENA-TN-0005

[RD08] ATHENA - ToO Reaction Architecture Trade-off, ATHENA-ESA-TN-0002

[RD09] ATHENA: The Advanced Telescope for High Energy Astrophysics: Mission Proposal, K Nandra et al 2014

[RD10] IXO Environmental Specification, Sørensen, J., Rodgers, D., Drolshagen, G., Santini, G., 2010

[RD11] Estimate of the impact of background particles on the X-ray Microcalorimeter Spectrometer on IXO, Nucl. Instrum. Methods Phys. Res. Sect. Accel. Spectrometers Detect. Assoc. Equip. 686, 31–37, Lotti, S., Perinati, E., Natalucci, L., Piro, L., Mineo, T., Colasanti, L., Macculi, C., 2012

[RD12] A magnetic diverter for charged particle background rejection in the SIMBOL-X telescope, in: Turner, M.J.L., Flanagan, K.A. (Eds.), p. 70112Y–70112Y–11. doi:10.1117/12.789917, Spiga, D., Fioretti, V., Bulgarelli, A., Dell'Orto, E., Foschini, L., Malaguti, G., Pareschi, G., Tagliaferri, G., Tiengo, A., 2008

[RD13] Timing accuracy and capabilities of XMM-Newton M. G. F. Kirsch et al Proc SPIE Vol. 5165 2004

[RD14] XMM Timing he relative and absolute timing accuracy of the EPIC-pn camera on XMM-Newton, from X-ray pulsations of the Crab and other pulsars A. Martin-Carrillo et al A&A 545, A126 (2012)

[RD15] *INTEGRAL* timing and localization performance R. Walter (arXiv:astro-ph/0309525v1)

[RD16] E. Serpell and F. Possanzini, *XMM-Newton Time Correlation*, XMM-OPS-RP-0026-TOS-OF Issue 1, 2003

[RD17] Absolute timing with IBIS, SPI and JEM-X aboard INTEGRAL. Crab main-pulse arrival times in radio, X-rays and high-energy gamma -rays , Astronomy and Astrophysics, v.411, p.L31-L36 L Kuiper, et al. Astronomy and Astrophysics, v.411, p.L31-L36 2003 (arXiv:astro-ph/0309178)

[RD18] Absolute Timing of the Crab Pulsar with the Rossi X-Ray Timing Explorer, A Rots et al. The Astrophysical Journal, Volume 605, Issue 2, pp. L129-L132, 2004 (arXiv:astro-ph/0403187)

[RD19] Jodrell Bank Crab Pulsar Monthly Ephemeris http://www.jb.man.ac.uk/pulsar/crab.html

[RD20] IXO AOCS Analyses. TEC-ENC/40.10. Issue 1.1, 27/09/2010.

[RD21] ATHENA_L1 Internal Study Report. SRE-PA/2011.033/NR. Issue 1.0, 22/06/2011.

[RD22] XMM NEWTON – Performance assessment of the XMM NEWTON Star Tracker and the On-Ground Attitude Reconstruction Process. Ref XMM-MOC-TN-0141-TOS-GFT 11/02/2004.

[RD23] ATHENA – CreMA, ESA-ATHENA-ESTEC-MIS-TN-0001.

[RD24] ATHENA – L2 Proposal.

[RD25] ATHENA – Mock Observing Plan, SRON-ATH-2014-001.

[RD26] ATHENA – Telescope Reference Design, ESA-ATHENA-ESTEC-PL-DD-0001, Issue 2.6.

[RD27] The Optical Design of the ATHENA+ Mirror: ATHENA+ Supporting Paper.

[RD28] Draft Programme Proposal on the Ariane Launcher Development Programmes for decision at CM-14, ESA/PB-LAU(2014)48, rev. 1, Annexes A and B, 17/10/2014.

[RD29] A5 User Manual Addendum: Modification of the Shock specification and the Shock qualification methodology. DC/BD/ST/JTH/MBe/L13.198.

[RD30] XMM-Newton Quarterly Mission Status & Performance Indicators, http://xmm.esac.esa.int/external/xmm_news/mission_status/index.php

[RD31] XMM-Newton Target of Opportunity (ToO), http://xmm.esac.esa.int/external/xmm_sched/too/index.php.

[RD32] Bonino, L., 2010. Preliminary instrument module contamination control plan (report n. 8).

[RD33] Collon, M., 2010. High-Performance X-ray optics. Abstract and Summary Report.

[RD34] Ferreira, D.D.M., Christensen, F.E., Jakobsen, A.C., Westergaard, N.J., Shortt, B., 2012. ATHENA optimized coating design, in: Takahashi, T., Murray, S.S., den Herder, J.-W.A. (Eds.), p. 84435L. doi:10.1117/12.925694

[RD35] Nandra, K., Barcons, X., Herder, J.-W. den, Barret, D., Fabian, A., Piro, L., 2013. ATHENA mission proposal.

[RD36] Oosterbroek, T., 2010. IXO Telescope and Mirror Assembly Reference Document.

[RD37] Oosterbroek, T., 2011. IXO: Molecular contamination on the mirror.

[RD38] Rando, N., 2010. Assumptions for estimating the effective area of the IXO telescope.

[RD39] Wille, E., 2011. ATHENA Mirror Module Design and Development Status.

[RD40] Willingale, R., Pareschi, G., 2013. The optical design of the Athena+ mirror.

[RD41] ATHENA – Operational aspects of response to ToO alerts and return to routine timeline activities, ESA-AMCO-MO-003, 31/03/2016.

[RD42] ATHENA – SWG2-1-TN-0003: Positional accuracy requirements for TP2.1 (high-z AGN), Issue 1.0, 14/04/2016.

[RD43] Margin philosophy for science assessment studies, SRE-PA/2011.097, Issue 2.0, 2/12/2014.

2 POINT SPREAD FUNCTION HEW

2.1 MRD Requirements

See the MRD.

2.2 Decomposition

On-target (0.2 - 7 keV) PSF: The achieved HEW will be the combination of the HEW provided by the SC to the focal-plane (taking into account all SC-level effects: primarily mirror-quality but also SC RKE), and the pixelation error caused by the pixel-array of the detectors. In-principle the WFI pixel-size has been selected to sufficiently over-sample the PSF such that the pixelation contribution is very small. For X-IFU the pixel-size is ~same as the PSF HEW, so there will be a significant contribution (capped to ≤1'' HEW).

Off-axis (0.2 - 7 keV) PSF: The off-axis PSF is passed to the SC.

High-energy (7 - 12 keV) PSF: The high-energy PSF is passed to the SC (negligible pixelation error).

Fast observations on-target (0.2 - 7 keV) PSF: The achieved HEW will be the combination of the HEW provided by the SC to the focal-plane, and a fixed off-set of the FC on the WFI instrument to achieve the required PSF-defocusing.

Defocused high spectral resolution observations on-target (0.2 - 7 keV) PSF: The required HEW will be provided by the SC to the focal-plane, through a 25 mm piston offset of the telescope Focal Length (i.e. reduced to 11975 mm TBC).

2.3 Derived Requirements

The initial decomposition is shown in the following figure.

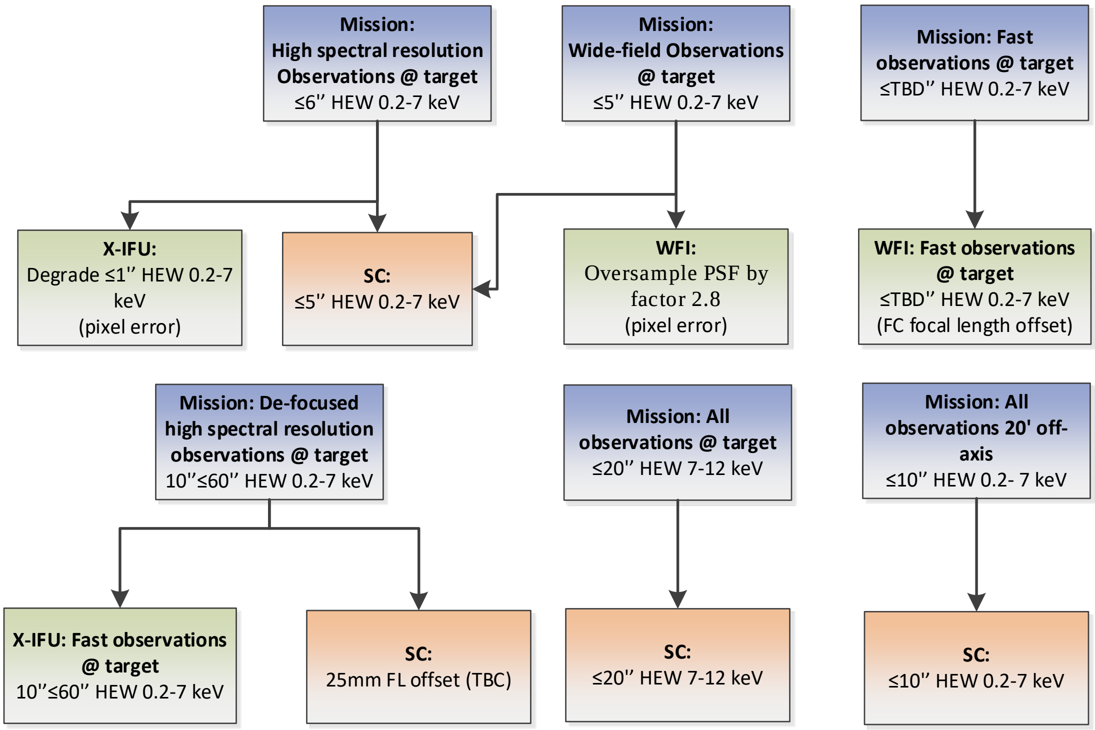

Figure 1: Decompositions for PSF HEW

3 OPERATIONAL AVAILABILITY

3.1 MRD Requirement

Requirement
The ATHENA Mission shall provide an operational availability of the science data product of greater than 85% averaged over the NoP and EoP.

Contingencies	Includes: a) time lost due to ground segment problems (slew parameters not computed in time, transmission drops, ground station antenna or link problems...) b) time lost because of spacecraft problems c) time lost due to instrument anomalies d) time not used because of Ground Station support to other spacecraft
Overheads	Time spent to configure the instruments at the start and end of each observation/exposure.
S/C-activities	Time where no activity could be scheduled. Such as planned tests, maintenance or calibration of star tracker, fine Sun Sensor, thruster torque etc. Extra post-slew margins requested for a few special manoeuvres. Problems with ground-station handovers. Special instrument tests that need to be manually commanded are also included here.
Slews	Time spent slewing between targets (includes star tracker field acquisition and locking on a guide star)
High radiation events	time lost due to high radiation coming from the sun (solar flares) or other sources (cosmic rays)

3.2 Decomposition

Note: this decomposition has been performed in BlockSim.

The operational availability requirements impact the ATHENA system as a whole (i.e. space, operational, and science segments). Therefore, an apportionment needs to be performed at lower level (Product Tree tier-1) such that the operational availability requirements are met for the science data products.

To perform the availability apportionment at tier 1 level, ATHENA is modelled as a series system. The apportionments take into account for each block an estimated static availability, the maximum achievable availability, and a predefined feasibility (easy, moderate, or hard) to achieve that level of availability. In addition, we need to specify the 'availability' of the environment, i.e. make an apportionment for when solar activity & GCRs is preventing observations (increased background).

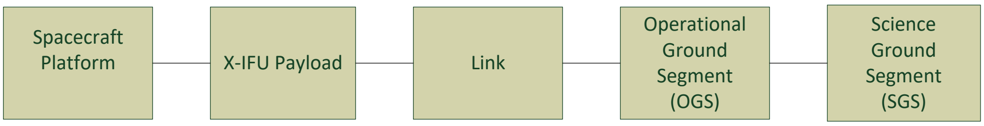

Figure 2: Availability Block Diagram for Type_1 Science Data (environment not shown)

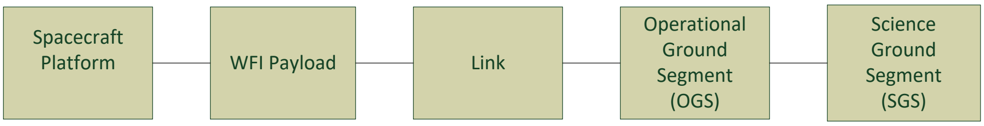

Figure 3: Availability Block Diagram for Type_2 Science Data (environment not shown)

In order to estimate the expected high-radiation ('environment') periods for ATHENA, values from the best (2014 Q3 – 0.95%) and worst case (2004 Q2 – 4.38%) quarters of XMM Newton data were used [RD30]. This leads to a reasonable allocation of 3%.

Tier-1 Product	Est. Operational Availability	Est. Maximum Achievable Operational Availability	Est. Pre-defined Feasibility	Optimum Apportionment
Environment	0.97	0.97	-	0.97
SC	0.85	0.9	Moderate	0.9
X-IFU	0.9	0.95	Hard	0.98
Link	0.99	0.9999	Moderate	0.999
OGS	0.95	0.999	Moderate	0.998
SGS	0.98	0.999	Hard	0.997
Type_1 Av.	0.68			0.85

Table 1: Tier 1 Availability Apportionment for Type_1 Science Data (Narrow Field)

Tier-1 Product	Est. Operational Availability	Est. Maximum Achievable Operational Availability	Est. Pre-defined Feasibility	Optimum Apportionment
Environment	0.97	0.97	-	0.97
SC	0.85	0.9	Moderate	0.9
WFI	0.9	0.95	Hard	0.98
Link	0.99	0.9999	Moderate	0.999
OGS	0.95	0.999	Moderate	0.998
SGS	0.98	0.999	Hard	0.997
Type_2 Av.	0.68			0.85

Table 2: Tier 1 Availability apportionment for Type_2 Science Data (Wide Field & Fast-Chip)

3.3 Derived Requirements

The decomposition is shown in the following figure.

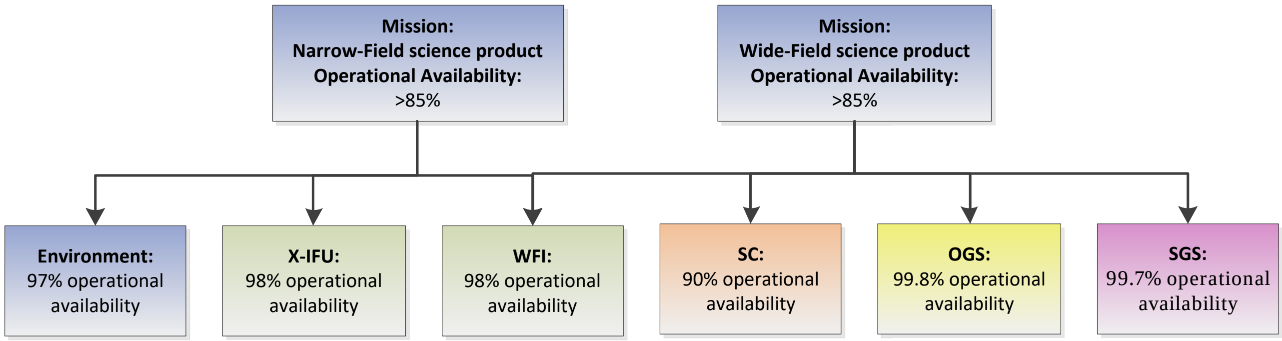

Figure 4: Decomposition of Operational Availability

Note: The defined availabilities for the instruments are with respect to their scheduled periods of observation, i.e. the X-IFU availability does not take into account the cooling-cycle, when the WFI will be observing.

4 NET OBSERVING TIMES

4.1 SciRD/ConOps Requirements

Note: the new Mock Observation List from the ASST corresponding to the 'CORE' design-point [RD25] does not make the categorisation used in the previous MoP (categories A, B, C & D), and only provides an observation list corresponding to the NoP, and so it is not currently possible to derive an EoP duration as per the previous version.

The current MoP provides a total observation duration, including calibration, of **107 Ms.**

4.2 Decomposition

Under the assumption that the SC is successfully delivered into the operational orbit and fully commissioned, meeting the net observing time requirements (during the NoP) and goals (during the EoP) will depend upon the availability of the ATHENA mission to perform science operations and produce the final science data product. The operational availability requirement is placed on the science data products as these are the ultimate mission product encompassing the entire system chain.

The decomposition/translation is from the net observing time specified in the Mock Observation List to (i) an overall ATHENA science data product availability (split into Narrow and Wide-Field products), and (ii) NoP and EoP durations, specified in the MRD.

The ATHENA science data product availability (A_0) is defined as an operational mean availability in accordance with [AD02]. This covers all possible sources of downtime and represents the average percentage of time that the science data product is available over the operating cycle.

$$A_0 = \frac{Uptime}{Operating\ Cycle}$$

Operational availability is a demonstrated (*a posteriori*) availability measure based on actual operational data. However, in the frame of the ATHENA project it shall be understood as the expectation of the science community in order to satisfy the scientific requirements of the mission.

We define the operating cycles for the Narrow-Field and Wide-Field observations as being the sum of those periods of the mission that are allocated to Narrow or Wide-Field observations.

Note: A_0=85% is considered an achievable number based upon previous IXO studies.

We define the operational availability requirements as:

- The operational availability of the Type_1 & Type_2 science data products shall be better than 85% averaged over the mission lifetime, i.e.:

$$A_{o\ type\_1} \geq 0.85$$

Only temporary random and deterministic system outages shall be considered as sources of downtime for the purpose of the operational availability computation. Examples of such temporary outages include but are not limited to:

- Random events: Weather related events; momentary service interruption after failure of nominal unit, single/multiple event upsets (SEU), or during system reconfiguration (e.g. switch to redundant unit) or re-initialization of the same unit (e.g. after SEU).
- Deterministic events: Science target acquisitions; payload calibrations; station keeping manoeuvres, etc.

Definitive system failures (reliability) shall not be considered.

Nominal (NoP) and extended (EoP) mission durations can then be derived from the observational requirements and the availability requirements as follows:

$$\frac{R_{type\_1}}{A_{0\ type\_1}} = NoP\_duration_{type\_1}$$

$$\frac{R_{type\_2}}{A_{0\ type\_2}} = NoP\_duration_{type\_2}$$

$$NoP\ duration = NoP\_duration_{type\_1} + NoP\_duration_{type\_2}$$

$$\frac{G_{type\_1} - R_{type\_1}}{A_{0\ type\_1}} = EoP\_duration_{type\_1}$$

$$\frac{G_{type\_2} - R_{type\_2}}{A_{0\ type\_2}} = EoP\_duration_{type\_2}$$

$$EoP\_dur = EoP\_duration_{type\_1} + EoP\_duration_{type\_2}$$

This results in the following NoP/EoP duration requirements.

Table 3: Summary of NoP/EoP duration requirements

NoP = 4 years

EoP = TBD

4.3 Derived Requirements

The decomposition is shown in the following figure.

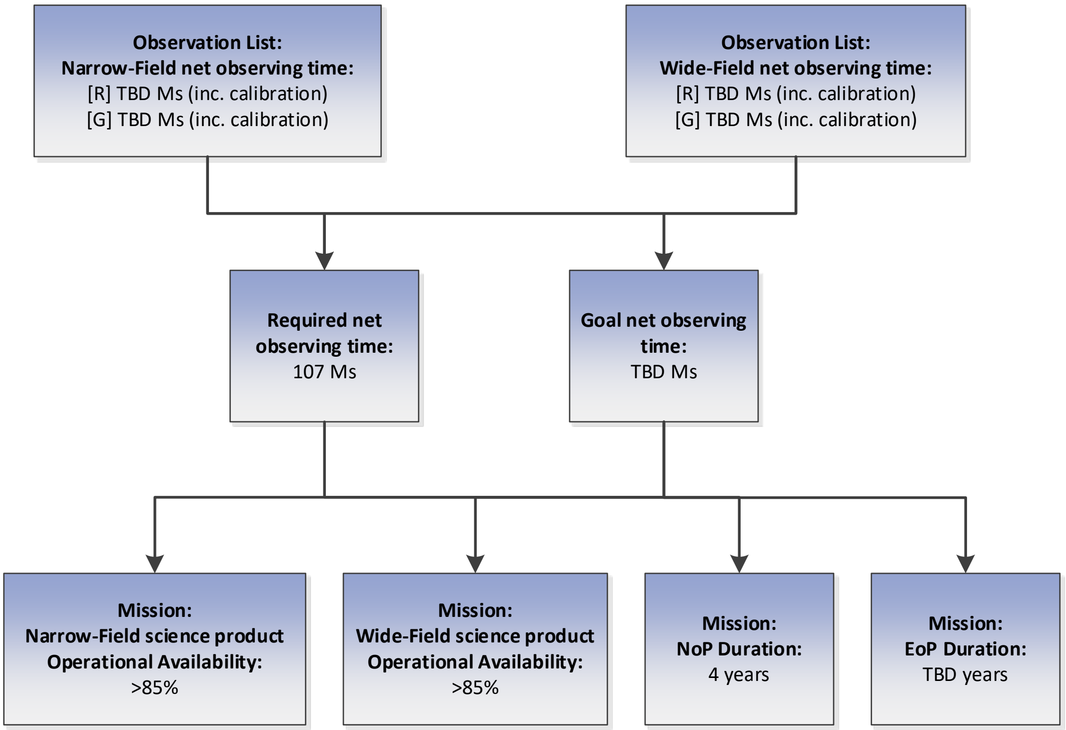

Figure 5: Net observing time decomposition

5 MISSION RELIABILITY

5.1 MRD Requirement

Requirement
The ATHENA Mission shall have a reliability (probability of continued successful delivery of both Narrow and Wide-Field observation data products to the end user) at the end of the NoP of 75%.

5.2 Decomposition

The reliability requirements impact the ATHENA system as a whole (i.e. space, operational, launch and science segments). Therefore, an apportionment needs to be performed at lower level (Product Tree tier-1) such that the overall reliability requirement is met.

Tier-1 Product	Apportionment
SC	0.90
X-IFU	0.90
WFI	0.95
OGS	1.00
SGS	1.00
LS	0.98
Narrow Field	**0.80**
Wide Field & Fast	**0.85**
Overall	**0.75**

Table 4: Tier 1 reliability apportionments for X-IFU, WFI and overall

5.3 Derived Requirements

The decomposition is shown in the following figure.

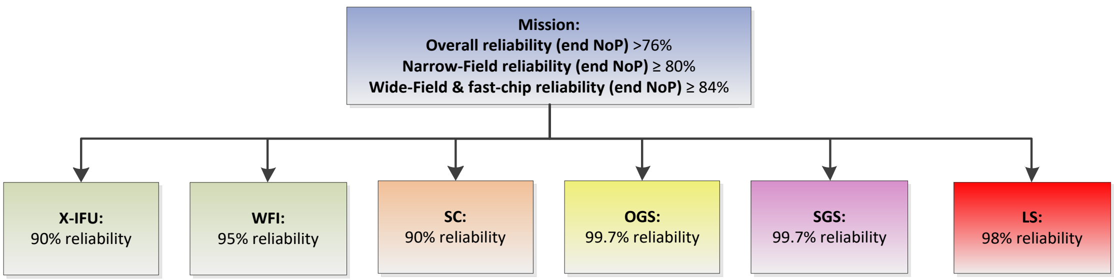

Figure 6: Decomposition of reliability

6 GRB TRIGGER EFFICIENCY

6.1 SciRD Requirement

Note: SciRD requirement R-SCIOBJ-261 states 25 WHIM observations via GRB-afterglows. The derivation of the requirement is now unclear and needs to be consolidated, as starting from 25 GRBs does not require 40% of all-sky GRBs over 4 years.

Note: no confidence-level has been associated with this requirement, but the implication is 50% cl. Poisson statistics would need to be used to attach a cl to the requirement.

6.2 Decomposition

GRB alerts are a subset of ToO alerts, i.e.:

$$GRB_{alerts} \in ToO_{alerts}$$

The following parameters can be defined:

$T_{mission}$	The duration of the operational mission (NoP.)
GRB_{obs}	The per-year total number of successful observations (40 over the duration of the mission; this is the science requirement.)
$GRB_{alerts/year}$	The total number of GRB-alerts (external) received by the ATHENA mission per year.
F_{cand}	The fraction of $GRB_{alerts/year}$ with sufficient x-ray flux 4 hours after receipt of the alert, and sufficiently localised, to perform SG4.1 science.
FoR	The fraction of sky accessible for TYPE_1 (Narrow-field) science observations.
GRB_{valid}	The number of GRB-alerts (external) with sufficient flux 4 hours after receipt, and in the FoR.
F_{accept}	The probability that the Project Scientist will accept the alert (SOC decision point.)
A_{inst}	The probability that the mission is able to pursue the GRB (MOC decision point.)
$GRB_{pursued}$	The number of GRB-alerts that are pursued.
ε_{resp}	The fraction of GRB_{alerts} for which the ATHENA mission is required to observe the GRB_{alert} within 4 hours.

Under the assumption of isotropic distribution of GRB_{alerts} in the sky[1], the following relationship to calculate GRB_{valid} can be stated:

[1] This allows the geometry of the FoR and the resulting sky coverage throughout the year to be ignored; this is a valid assumption because GRBs are extra-galactic in origin.

$$GRB_{valid} = T_{mission} \times GRB_{alerts/year} \times F_{cand} \times FoR$$

The value of $GRB_{pursued}$ can then be determined by considering the SOC and MOC decision points.

$$GRB_{pursued} = GRB_{valid} \times F_{accept} \times A_{inst}$$

Leading to the equation for ε_{resp}.

$$\varepsilon_{resp} = \frac{GRB_{obs}}{GRB_{pursued}}$$

Given that $GRB_{alerts/year}$ and F_{cand} are parameters external to the Mission architecture, and assuming $A_{inst} = 0.85$ and $F_{accept} = 0.98$, the resulting trade-space between FoR, ε_{resp} and NoP duration is shown in the following figure.

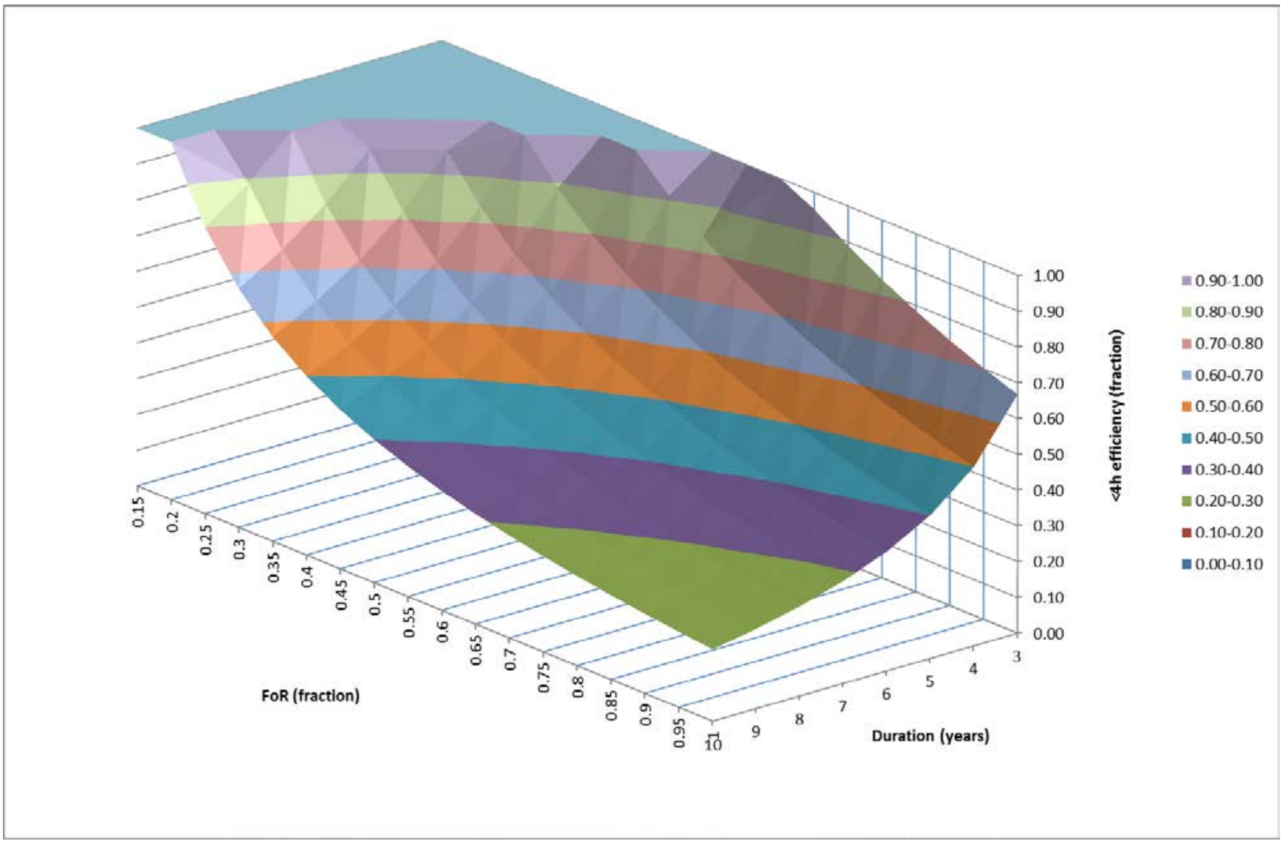

Figure 7: Relationship between FoR, $T_{mission}$ and resulting ε_{resp} in pursuit of the requirement (over the flat-top area the requirement for 40 GRBs over the NoP cannot be met)

Table 5: Relationship between FoR, $T_{mission}$ and resulting ε_{resp} in pursuit of the requirement (1.00 indicates the flat-top area where the requirement for 40 GRBs over the NoP cannot be met.)

FoR [fraction]	NoP Duration [years] 3	4	5	6	7	8	9	10
1	0.67	0.50	0.40	0.33	0.29	0.25	0.22	0.20
0.95	0.70	0.53	0.42	0.35	0.30	0.26	0.23	0.21
0.9	0.74	0.56	0.44	0.37	0.32	0.28	0.25	0.22
0.85	0.78	0.59	0.47	0.39	0.34	0.29	0.26	0.24
0.8	0.83	0.63	0.50	0.42	0.36	0.31	0.28	0.25
0.75	0.89	0.67	0.53	0.44	0.38	0.33	0.30	0.27
0.7	0.95	0.71	0.57	0.48	0.41	0.36	0.32	0.29
0.65	1.00	0.77	0.62	0.51	0.44	0.38	0.34	0.31
0.6	1.00	0.83	0.67	0.56	0.48	0.42	0.37	0.33
0.55	1.00	0.91	0.73	0.61	0.52	0.45	0.40	0.36
0.5	1.00	1.00	0.80	0.67	0.57	0.50	0.44	0.40
0.45	1.00	1.00	0.89	0.74	0.64	0.56	0.49	0.44
0.4	1.00	1.00	1.00	0.83	0.71	0.63	0.56	0.50
0.35	1.00	1.00	1.00	0.95	0.82	0.71	0.64	0.57
0.3	1.00	1.00	1.00	1.00	0.95	0.83	0.74	0.67
0.25	1.00	1.00	1.00	1.00	1.00	1.00	0.89	0.80
0.2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The proposed implementation is a 60% FoR, 5 year NoP (note that in §2.3, the NoP is set to 5 years even though the derivation from the Mock Observing Plan results in 4 years), resulting in $\varepsilon_{resp} = 0.67$ (green in the table above). We can note from the above figure and table that extensions in the operational phase considered, or increases in the FoR, will improve the statistics of captured GRBs considerably, and allow a corresponding relaxation in the response requirement, which will be difficult to meet.

Parameter name	Definition	Quantity	Justification	Comment
<Mission Duration>	Duration in years.	5	From the proposal: ATHENA has a baseline mission lifetime of 5 years, although for such an ambitious mission, consumables should be sized to enable an extension of at least 5 more years. A preliminary mock observation plan has been assembled using typical targets for both the driving science and the observatory science. Considering a conservative observing efficiency of 75%, this shows that ATHENA can reach the science goals of the Hot and Energetic Universe theme during the baseline mission, while preserving a large fraction (30-40%) of the available time for observatory science.	Better justification to come from the core and observatory net observing time requirements. Currently 5 years - information in proposal implies 890 days core science, 479 days observatory (assuming 65/35 split and 75% eff.) If the requirement on 40 GRBs is made a goal can use 10 years here?
<GRB_alerts_year>	All sky total GRB-alerts received by the SGS per year.	200	A pool of 200 GRBs per year, expected from external GRB triggers in the ATHENA era.	Some sort of justification is going to be required, based on expected facilities etc. This number drives the breakdown so is very important. A list of facilities is provided (LOFAR, SKA, ALMA, JWST etc.) which will be the sources of the triggers.
<GRB_alerts_total>	All sky total GRB-alerts received by the SGS over the NoP.	1000	Calculated.	At 50% confidence level (poisson statistics)
<F_cand>	Fraction of <GRB_alerts_total> (i) with sufficient x-ray fluence 4 hours after receipt, and (ii) sufficiently localised to allow SG4.1 science to be conducted.	0.12	From the proposal: Assuming that 12% of the 200 GRBs will have sufficient fluence 4 hours after the trigger.	The assumption is that the validation pre-conditions for F_cand are: (i) the flux of the GRB-event (in detection band) **at the time of receipt** - correlated with the x-ray fluence, otherwise the observatory will need to respond to ~100 ToOs per year assuming 50% FoR. (ii) sufficiently localised (3' to allow acquisition with X-IFU.) This fraction, supplied by the scientists, should also take into account the <time between the external observation and ToO-alert receipt at ESAC>, i.e. the latency in the alert-provider. They won't be able to impose any requirements on the ToO-suppliers, as they are outside the system.

Parameter name	Definition	Quantity	Justification	Comment
<FoR>	Fraction of the sky accessible with the observatory.	0.6	Implementation requirement on mission, derived from above.	Because of the isotropy assumption on GRB-locations, there is no need to specify the geometry of FoR. If we move away from the isotropic assumption, then the geometry of the FoR will need to be taken into account when specifying (i.e. switch to +/- xdeg.) (example: if the locations where always at the poles, then they would always be accessible; alternatively if they were distributed on the circumference of the ecliptic, they would only be accessible 1/3rd of the time.) Note that GS processing of GO observations requirement (25 days) from previous SciRD was linked to the FoR geometry, to allow re-observation if something goes wrong. Don't see this in the proposal yet. Note that there is no apparent reason why anti-sun direction pointing cannot be achieved (giving 75% FoR), but will require rotating solar arrays of course.
<valid_GRB_alerts>	Number of <GRB_alerts_total> (i) with sufficient fluence 4 hours after receipt, and (ii) sufficiently localised to allow SG4.1 science to be conducted, (iii) in FoR.	72	Calculated.	This is the quantity to which 'GRB efficiency' of 40% applies to in the proposal. Assuming isotropic distribution of GRB-locations, this equation is valid for all FoR geometries. A move away from isotropy will affect this number. However, probably one should imagine the source distribution for TOOs is not uniform - (i) depending on what the triggering facility is, and (ii) key measurement is looking at features in the soft X-ray band where galactic absorption may be confusing. THEREFORE it could be that we concentrate on TOOs with galactic latitude > 30 degrees (TBC). My current understanding is that a move away from isotropy will, when combined with the geometry of the FoR, affect the statistics of the ToO being in the FoR. A simple example is that if they always occur at the galactic poles, then they will always be in the FoR. The form of the spatial distribution of ToOs is an output of the SST, and will, when fed through the decomposition, modify the statistics and ultimately the requirement for less than 4 hours for 80% of cases (i.e. may be reduced to 60% of cases or something) - so very important to get a good handle on with the scientists as it may influence the chosen solution significantly.

Parameter name	Definition	Quantity	Justification	Comment
<F_accept>	Fraction of F_cand that are selected for pursuit by PS.	0.98	Some function of the nominal observing plan.	Represents PS decision to not pursue ToO based on current observation importance (i.e. some small % of valid ToO-requests will be refused because the current observation is more important.) Note that this decision is taken w/o any knowledge of the predicted state of the SC (X-IFU). At the moment assume we chase the GRB even though we will not always meet the requirement - ASK the scientists!
<Inst_availability>	Probability that the ATHENA mission is available to pursue the GRB.	0.85	Same as Type#1 observation availability.	This is not the same as the mean operational availability - it is more like the MOC decision point (analogous to the SOC PS decision factor), and will take into account OCMs, calibration campaigns etc., but not for example slewing. This factor may not be included here depending on the fidelity of the simulation. It can also go into the ToO simulation. This factor may include the decision not to proceed if X-IFU is not going to be available in a reasonable timeframe.
<pursuable_GRBs>	Number of <valid_GRB_alerts> that are pursued, i.e. (i) not rejected by PS, (ii) occurring during available periods.	59.976	Calculated.	
ε_resp	Fraction of <pursued_GRBs> for which **the mission** must observe the ToO within 4 hours.	0.67	Implementation requirement on the mission, derived from above.	Named Ground Segment efficiency in proposal - this is wrong because it is a mission requirement (not just GS). This is going to include everything in the chain and is the true requirement to be placed on the ATHENA+ mission.
<SG4.1 observed GRBs>	GRBs, with sufficient fluence 4 hours after the trigger, observed with X-IFU within 4 hours of the trigger.	40	From the proposal: SG4.1 requires 40 distant GRB-afterglow observations.	Science Requirement - this will need to be reduced at some point? Best approach would be to make it a goal (i.e. applicable over NoP+EoP). - 50 for proxy statistics.

Table 6: Budget for GRB efficiency decomposition ([G] FoR case)

6.3 Derived Requirements

The derived requirements are shown in the following figures for the two cases which combine the goals and requirements on FoR and ToO-response, both for a 5 year NoP.

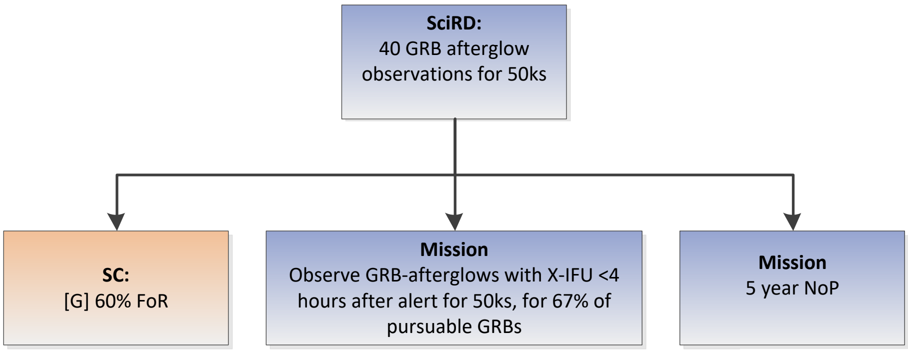

Figure 8: GRB trigger efficiency decomposition ([G] FoR case)

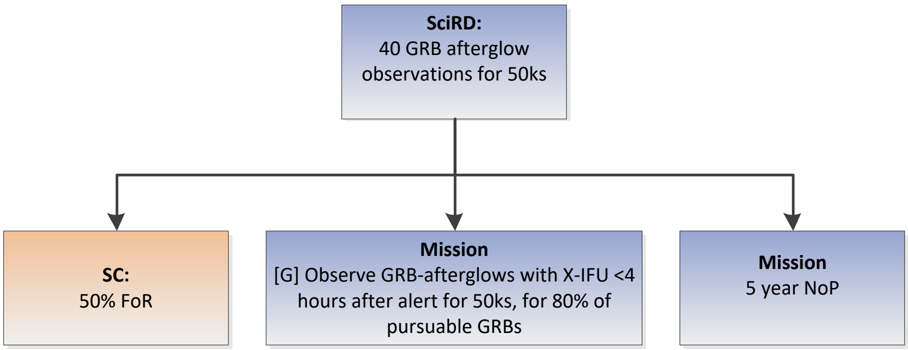

Figure 9: GRB trigger efficiency decomposition ([G] ToO-response case)

Notes:

Note the meaning of 'pursuable'! This is a GRB that meets all the criteria for pursuit; it does not imply that it is pursued (modelling will reveal that some are not reachable within a reasonable time so will not be pursued).

Scheduling constraints could be imposed to improve system-reactivity for a constrained architecture, e.g. synchronise X-IFU nominal observations (cooling cycle) to GS-visibility/availability – but this is a big constraint.

Or schedule OCMs, other interruptions to occur whilst the X-IFU is down (an OCM timescale ~same as cooling cycle down-time), although the benefit will be slight and probably not worth the additional operational complexity.

7 EFFECTIVE AREA & GRASP

Note: Unlike the previous issue of the MBD, the entire Effective Area of the SC is specified to the Prime, which now has control over all terms which contribute to this (Mirror A_eff, SC pointing & misalignment contributions). This chapter aims at providing examples of the decomposition under SC Prime Control.

Note: The Effective Area and Grasp decomposition is performed using the achievable values from the SC and PL under the current assumptions – accordingly there are mismatches between the SciRD and the MRD requirements, which are identified.

7.1 MRD Requirements

See the MRD.

7.2 Effective Area Decomposition

7.2.1 Narrow-Field observations

The Effective Area of Narrow-Field observations on the telescope LoS at an x-ray energy e [$A_{eff\_NF}(e)$], is a product of the Effective Area provided to the focal plane by the SC [$A_{eff\_SC}(e)$], and the 'Instrument Efficiency' of the X-IFU [$Q_{WFI}(e)$], including all effects at PL-level (detector and filter).

$$A_{eff\_NF}(e) = A_{eff\_SC}(e).\, Q_{X-IFU}(e)$$

7.2.2 Wide-Field observations

The Effective Area of Wide-Field observations at an x-ray energy e [$A_{eff\_WF}(e)$], is a product of the Effective Area provided to the focal plane by the SC [$A_{eff\_SC}(e)$], a vignetting correction factor [$V(e)$] in the case of the specification of the integrated Effective Area over the Wide-Field FoV, and the 'Instrument Efficiency' of the WFI [$Q_{WFI}(e)$], including all effects at instrument-level (detector and filter).

$$A_{eff\_WF}(e) = A_{eff\_SC}(e).\, V(e).\, Q_{WFI}(e)$$

For the Grasp requirements, we multiply the FoV-averaged response by the solid angle FoV of the WFI instrument:

$$G = A_{eff\_WF\_average}(e) \cdot \Omega$$

7.2.3 SC Effective Area (Example Decomposition)

The Effective Area provided by the SC is the product of the MA Effective Area on the MA optical axis (including all internal misalignments, contamination etc.), multiplied by a reducing factor to account for the vignetting effects of any global pointing misalignments, i.e.:

$$A_{eff\_SC}(e) = A_{eff\_mirror}(e).\, P_{SC}(e)$$

7.2.3.1 SC-Level Effects

Note: This section outlines the approach used in the CDF study to quantify [$P_{SC}(e)$].

In the CDF we introduced a reducing factor to account for the vignetting effects of any pointing misalignments, $[P_{SC}(e)]$, set at <2% at all energies up to 10 keV. Two effects were considered:

- The LoS effective area of the telescope will be modulated (reduced) by any mis-alignment between the telescope LoS and the optical axis of the MA – this will be caused by any relative change in the geometry between the Mirror and the focal plane of the instrument (α)
- Additionally, because the target will not be located precisely on the telescope LoS (APE error - β), an additional vignetting term can be present to further reduce the A_eff at the target itself.

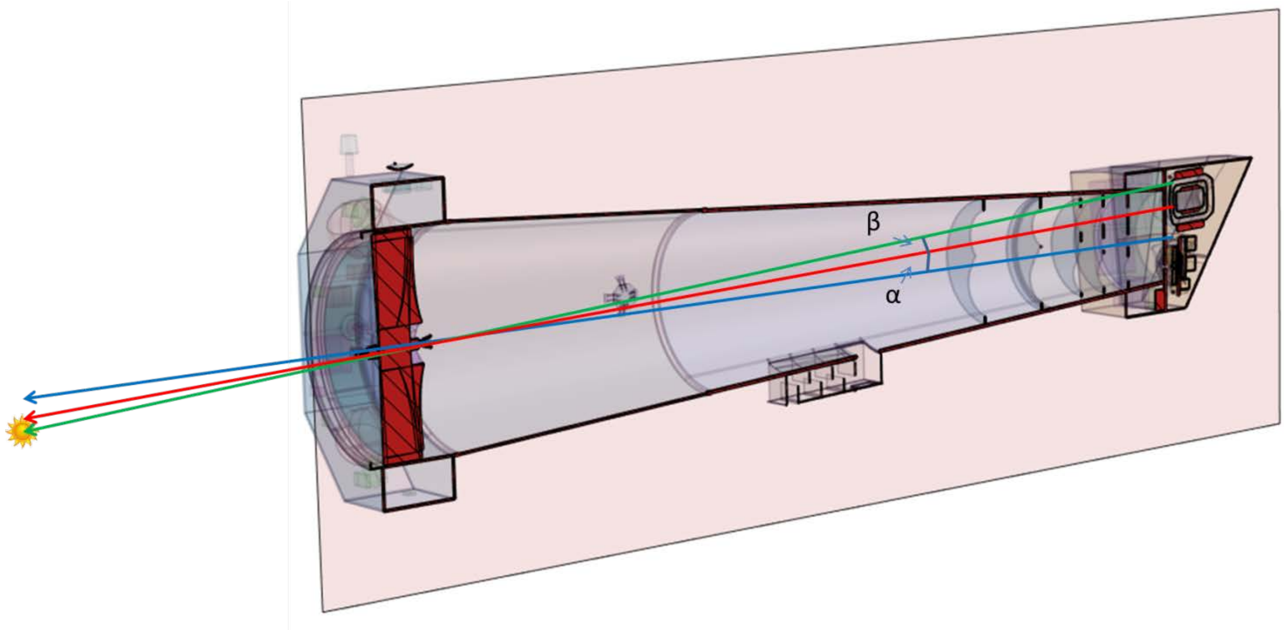

Figure 10: Optical axis (blue) and LoS (red) mi-alignment (σ), and LoS APE (β) will cause vignetting at the target

This variation will have two undesirable effects: A reduction in effective area, and a variation in effective area, which may be important for science related to X-ray timing, and would imply control of the instrument intrinsic effective area variation to a small level compared to the source variation that is being observed (and at the frequencies of interest.)

Figure 11 shows the vignetting parallel and perpendicular to the reflection plane for a reference telescope design. Figure 12 shows an equivalent vignetting curve calculated using the ESA reference telescope model.

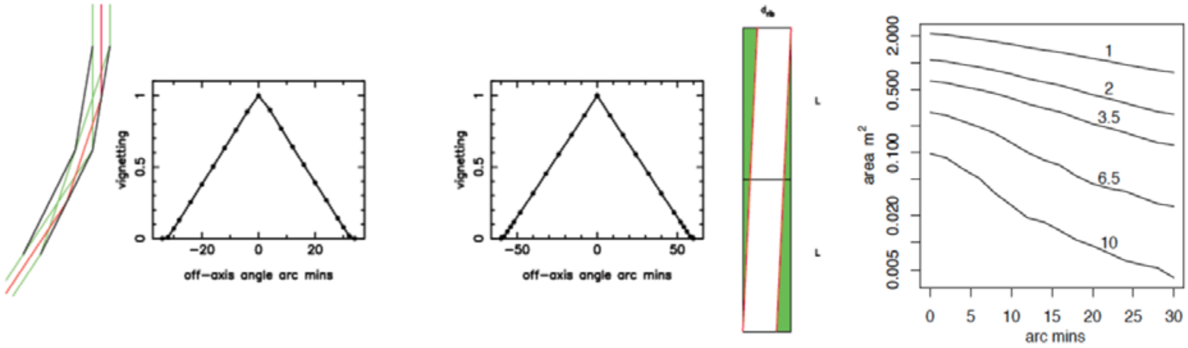

Figure 11: [left, middle] vignetting functions parallel and perpendicular to the reflection plane; [right] effective area loss at various energies as a function of off-axis angle

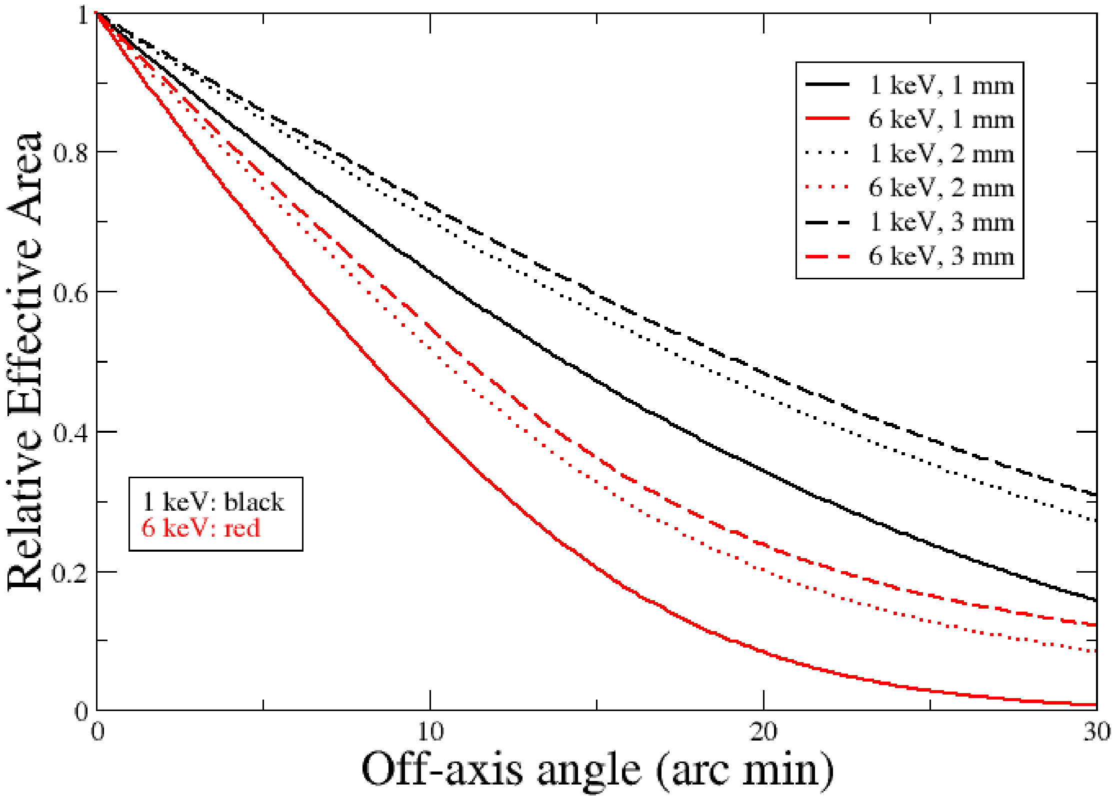

Figure 12: SC vignetting as a function of off-axis angle from the reference telescope model [RD26]

In the CDF, a preliminary requirement was set to restrict the effective area loss at the target due to vignetting to less than 2% at all energies.

Note: this corresponds to an initial calculation for the angle resulting in 1% loss at 10 keV for the reference telescope with 1mm rib-spacing – see Figure 14. The calculation was performed using the reference telescope model 10[RD26], with the following results for the angular error corresponding to 1% effective area loss due to vignetting:

- *1 keV 0.3 arc min= 18"*
- *6 keV 0.2 arc min = 12"*

- *10 keV 0.15 arc min = 9''*

A 20" value was taken, corresponding to 10 keV (the worst-case energy), which for the CDF study was split into a 10" error on the APE between the LoS and Optical Axis of the telescope, and the 10" APE requirement, driven by the WFI Window mode.

A preliminary requirement was set in the CDF study to achieve a knowledge of the variation of Mirror Effective Area at the target to better than 1% of the instantaneous peak response at all energies. This requirement has currently been removed from the baseline requirements (in any case the 2% limit on vignetting loss provides also a knowledge within 2%).

Note: this translated to the 7" AKE requirement between the target and the optical axis in the CDF study, under the assumption that the mirror vignetting function is well characterised.

7.2.3.2 Mirror Level Effects

Note: This section outlines the approach used in the CDF study to quantify [$A_{eff\_mirror}(e)$].

The MA Effective Area is calculated using the Reference Effective Area estimate in [RD26]. The following figure shows the *design* (i.e. assuming no losses) A_eff spectrum of the (at time of CDF) 15-row reference mirror for three different rib-pitch values.

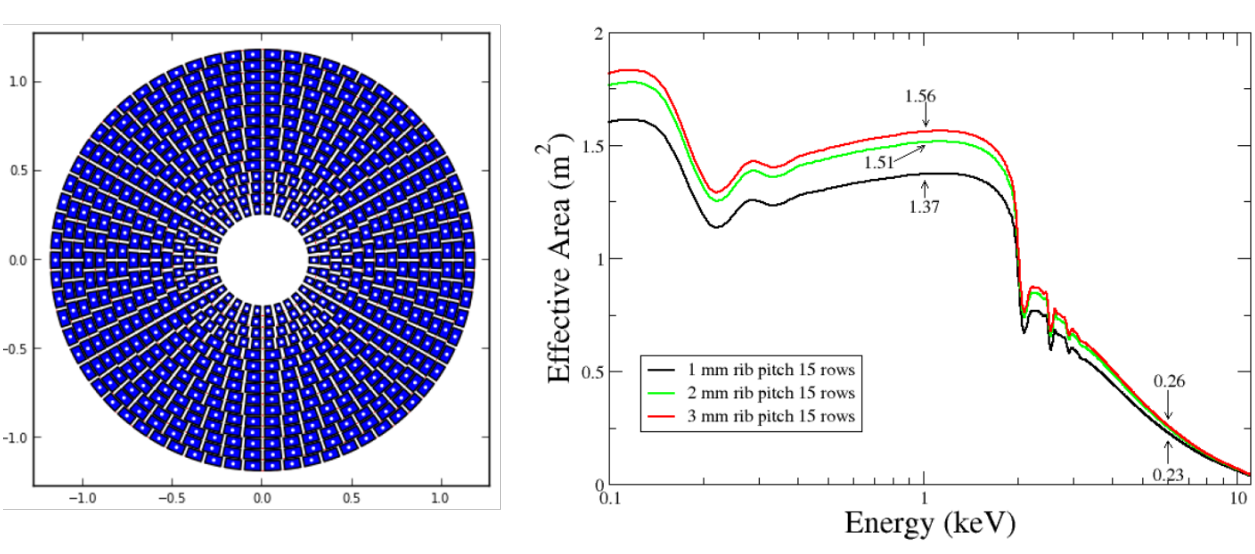

Figure 13: Reference MA layout and A_eff from [RD26]

A number of effects potentially contributing to a reduction of the MA Effective Area were identified in the context of IXO (see table below from [RD38]). To each effect was allocated a reduction in A_{eff} on the basis of preliminary assumptions/analysis.

$$\boldsymbol{A_{eff\_mirror}}(e) = \left(1 - L_{A_{eff_{ext\_obs}}} - L_{A_{eff_{int\_obs}}} - L_{A_{eff_{coat\_imp}}} - L_{A_{eff_{cont\_BoL}}}\right) \cdot \boldsymbol{A_{eff_{design}}}(\boldsymbol{e})$$

Table 7: Mirror effective area reduction budget for IXO

Parameter	Value	Comment	Impact

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$L_{A_{eff_{ext\_obs}}}$	0	**External obscuration:** Obscuration induced by elements external, mounted in front of the MM already considered in $A_{eff_{design}}$	τ
$L_{A_{eff_{int\_obs}}}$	0.05	**Internal obscuration:** Misalignment of MM on petal (0.01) Misalignment upp./low. Stack (0.02) Design obscuration factor (0.01) Stack manufacturing error (0.01)	τ $\frac{l_{opt}(f,r)}{l_{plate}}$
$L_{A_{eff_{coat\_imp}}}$	0.01	**Coating imperfections:** uncoated areas, e.g. close to bonding areas/ribs (0.08) coating layer variations, layer thickness and density uniformity (0.02)	$R(E)$
$L_{A_{eff_{cont\_BoL}}}$	0.04	**Contamination effects:** Particulate, based on 100 ppm (BoL) (0.04) Molecular, depends on energy, based on <1e-7 gr/cm2 (BoL) (0)	$R(E)$

These allocations are in the process of being revisited in the context of ATHENA, considering both optics technology advances and further system (platform) design definition.

7.2.3.2.1 Effect of Contamination

A contaminant is any material in the whole light path of an instrument that should not be there and which affects the efficiency of the instrument. This can be, in the simplest case, frozen water showing-up as oxygen features in spectra, or it might be any other substance that might out-gas from the spacecraft and freeze onto any of the instruments. The two main categories of contamination are particulate contamination, and molecular contamination.

Table 8: Sources of contamination during the different lifecycle phases

Mission Phase	Molecular	Particulate
Fabrication	materials outgassing, machining oils, fingerprints, air fallout	shedding, flaking, metal chips, filings, air fallout, personnel
Assembly & Integration	air fallout, outgassing, personnel, cleaning, solvents, soldering, lubricants, bagging material	air fallout, personnel, soldering, drilling, bagging material, shedding, flaking
Test	air fallout, outgassing, personnel, test facilities, purges	air fallout, personnel, test facilities, purges, shedding, flaking, redistribution
Storage	bagging material, outgassing,	bagging material, purges,

	purges, containers	containers, shedding, flaking
Transport	bagging material, outgassing, purges, containers	bagging material, purges, containers, vibration, shedding, flaking
Launch site	bagging material, air fallout, outgassing, personnel, purges	bagging material, air fallout, personnel, shedding, flaking, checkout activities, other payload activities
Launch/Ascent	outgassing, venting, engines, companion payloads separation maneuvers	vibration and/or redistribution, venting, shedding, flaking
On-orbit	outgassing, UV interactions, atomic oxygen, propulsion systems	spacecraft cloud, micrometeoroid & debris impingement, material erosion, redistribution, shedding, flaking, operational events

7.2.3.2.2 Particulate Contamination

The particulate contamination for IXO has been estimated in [RD37]. Similar results are expected for ATHENA.

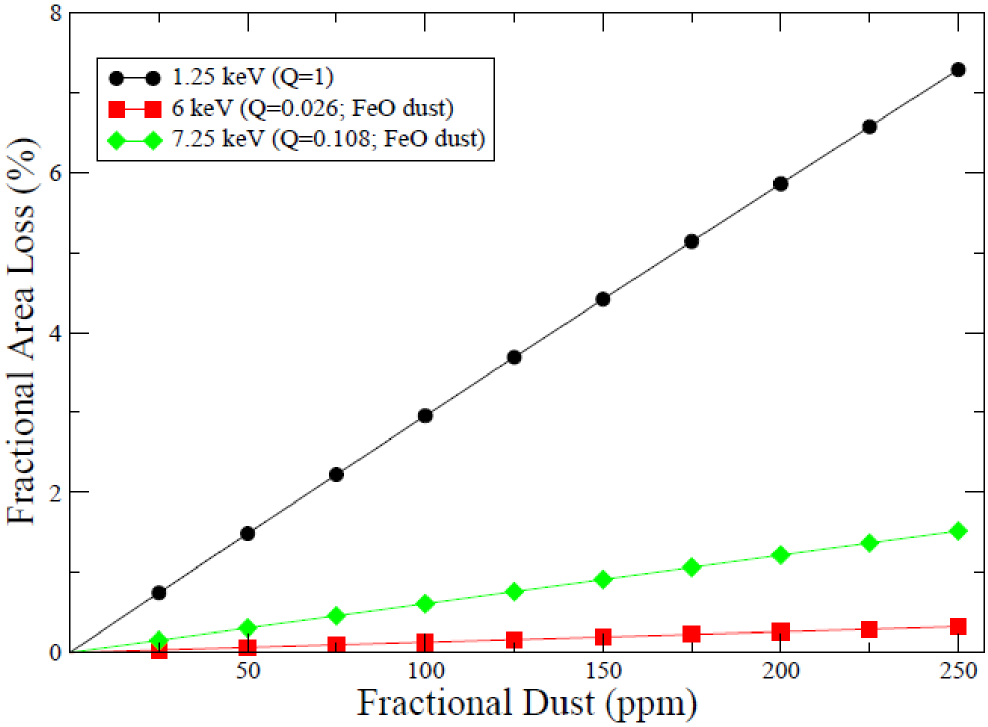

Figure 14: The loss in effective area (expressed as a percentage) as a function of fractional dust contamination for various cases: 1 keV with completely opaque particles (Q=1), 6 keV assuming FeO particles (Q=0.026), and 7.25 keV (just above the Fe K edge) also with FeO particles (Q=0.108). Particulate contamination can be estimated by a simple parametric equation (in the range 0–250 ppm):

$$L_{A_{eff_{particulate\_cont}}} = 0.0293 \cdot F_{particulate}(ppm)$$

Where:

- $L_{A_{eff_{particulate\_cont}}}$ is the loss in MM effective area due to particulate contamination

- $F_{particulate}(ppm)$ is the fractional level of contamination.

For a design with 125 ppm particulate contamination, the expected loss of effective area can be around 4%.

7.2.3.2.3 Molecular Contamination

Water deposition on the surface of the mirror will not be considered here since the temperature of the mirror surface (around 293 K) is sufficiently high that this is unlikely to contribute significantly. At the moment we apply a limit of <1e-7 g/cm^2.

7.2.3.2.4 Example Budget

The effects discussed previously can be organised into those occurring prior to MM-delivery to the SC, and those occurring thereafter.

Table 9: Example budget split for Effective Area loss

Parameter	Value [fraction]	Comment/reference
Pre-delivery	**0.07**	
Internally-caused obscuration	0.04	
Mis-alignment upper/lower stack	0.02	
Design obscuration factor	0.01	Baffling introduced by the fact that the MM length is sized for the inner most pore
Stack manufacturing error	0.01	
Coating imperfections	0.01	
Uncoated areas, e.g. close to bonding areas/ribs	0.008	
Coating layer variations, layer thickness and density	0.002	
Contamination effects	0.02	
Particulate	0.02	Based on Oesterbroek, 50ppm
Molecular	0	Based on <1e-7 g/cm^2
Post-delivery	**0.03**	
Externally-caused obscuration	0.01	Will drive MM integration rx, ry
External elements, mounted before or after the MMs	0	
Misalignment of the MM onto the MS	0.01	
Contamination effects	0.02	
Particulate	0.02	Based on Oesterbroek, 50ppm
Molecular	0	Based on <1e-7 g/cm^2
Total	**0.1**	

7.3 Derived Requirements

Considering the previous discussions, the following figures and table summarise the decomposition of the MRD Effective Area and grasp requirements (all applicable at the beginning of the NoP) into requirements placed on the SC and X-IFU/WFI instruments.

- Overall Effective Areas for X-IFU & WFI observations of narrow field targets, based on an assumed 10% reduction in A_eff due to Mirror-level effects (§7.2.3.2 – note this 10% reduction has now been removed from the reference Telescope document [RD26]), and an additional assumed 2% reduction due to vignetting effects (§7.2.3.1) – note that the vignetting curves are strongly dependent on the rib-pitch (vignetting curves to be used are provided in [RD26]).
- Grasp for WFI observations with wide field targets. Note that the grasp is not flown down to the SRD as it is mainly driven by the MM vignetting function and so largely out of the control of the SC Prime.

Note: All allocations below SC-level are indicated with a dashed line in the diagrams and should be considered as examples of the decomposition to be performed by the Prime, similar to the previous discussion. The colours of the boxes indicate the applicability of the requirement. Blue = Mission level (ESA), Green = PL level (PL consortia), Orange = SC level (SC prime) and Pink = MM level (MM provider).

Table 10: Breakdown of on-axis Effective Area requirements

Energy [keV]	0.2	0.35	1	7	10
Telescope Design A_eff [m^2] as per reference layout i2.7	2.23	1.81	1.87	0.228	0.089
Assumed losses:	12%	12%	12%	12%	12%
MM-level @ delivery to SC [%]	7%	7%	7%	7%	7%
SC Mirror-level effects [%]	3%	3%	3%	3%	3%
SC-level effects [%]	2%	2%	2%	2%	2%
ΣMM_Req @ delivery to SC [m^2]	**2.074**	**1.683**	**1.739**	**0.212**	**0.083**
SC_Req: Telescope A_eff [m^2]	**1.962**	**1.593**	**1.646**	**0.201**	**0.078**
WFI_Req: WFI Instrument Efficiency [%]	5.8%		85.0%	87.0%	55.0%
X-IFU_Req: X-IFU Instrument Efficiency [%]		17.0%	67.0%	72.0%	46.0%
MRD_Req: WFI overall A_eff [m^2]	**0.114**		**1.399**	**0.175**	**0.043**
MRD_Req: X-IFU overall A_eff [m^2]		**0.271**	**1.103**	**0.144**	**0.036**
SciRD_Req: WFI overall A_eff [m^2]- v2.5	0.069		1.250	0.180	0.040
WFI Areas Δ SciRD>MRD [%]	**65%**		**12%**	**-3%**	**8%**
SciRD_Req: X-IFU overall A_eff [m^2] - v2.5		0.105	1.050	0.160	0.030
X-IFU Areas Δ SciRD>MRD [%]		**158%**	**5%**	**-10%**	**20%**

With the MM-layout & reference MM A_eff values as per [RD26] issue 2.7, and the assumed contamination losses and SC-level losses in the breakdown, the SciRD requirements are significantly surpassed at low energies, but non-compliant particularly for the 7 keV Effective Area.

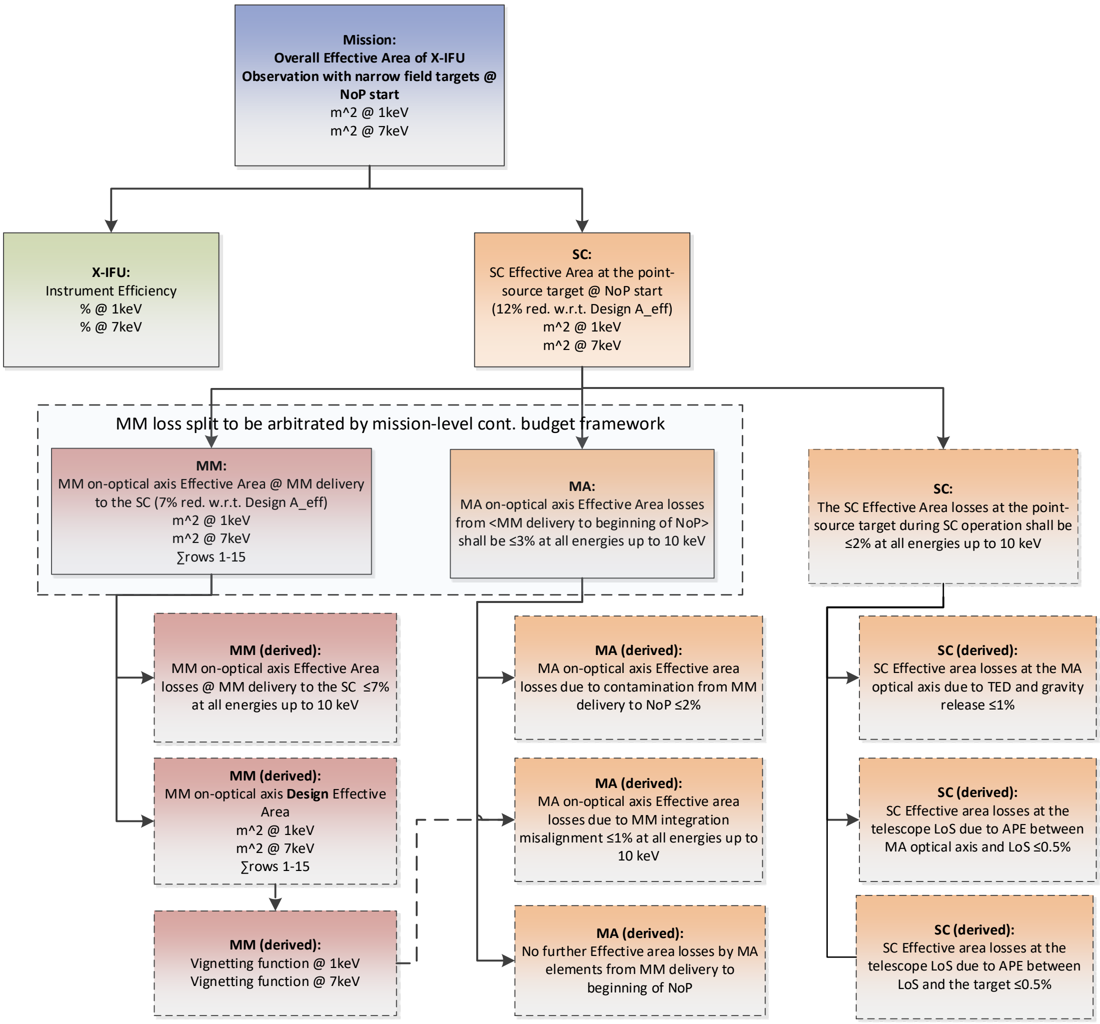

Figure 15: Example decomposition of the overall effective area for X-IFU observations with narrow field targets assuming the MM A_eff reported in [RD26] (red text is the original SciRD requirement).

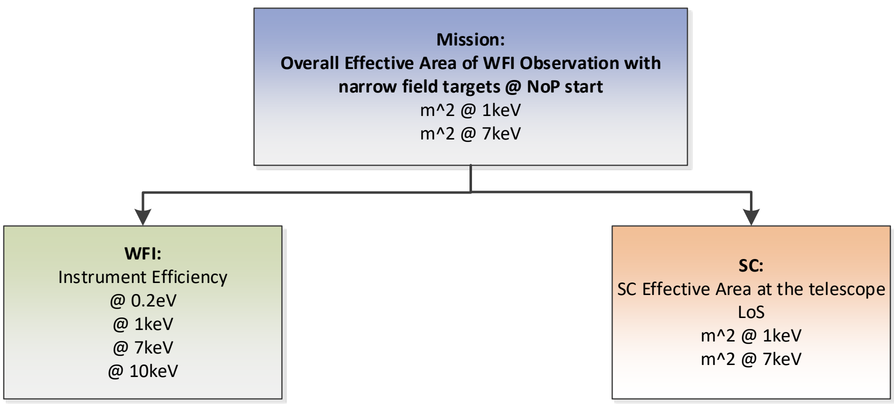

Figure 16: Summary of the decomposition of the overall effective area for WFI observations with narrow field targets (red text is the original SciRD requirement).

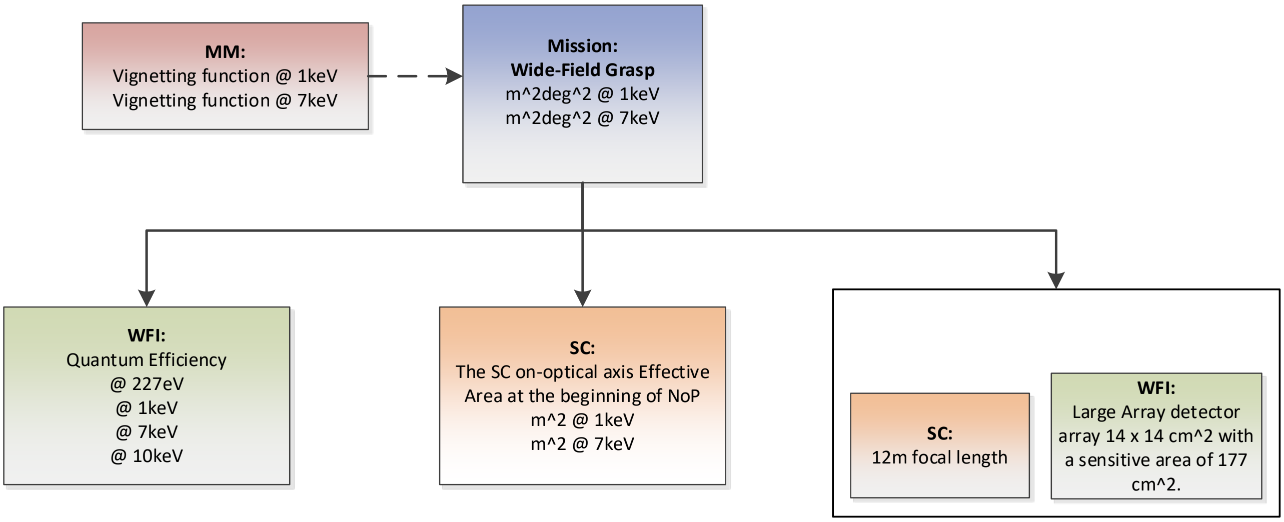

Figure 17: Summary of grasp for WFI observations with wide field targets.

8 EFFECTIVE AREA LOSS

8.1 MRD Requirements

Requirement
The ATHENA Mission shall undergo a change of the Effective Area between begin-of-life and end-of-life shall be less than 10% at 0.3 keV (TBC) on target.

8.2 Decomposition

8.2.1 Overall Effective Area

Recalling equation 15 for the Overall Effective Area at energy e:

$$A_{eff\_NF}(e) = A_{eff\_SC}(e).Q_{X-IFU}(e).P_{SC}(e)$$

The error in Effective Area at an energy e is the product of the errors of the individual terms in the above equation; We make the following initial distribution of the 10% over the system (all TBC).

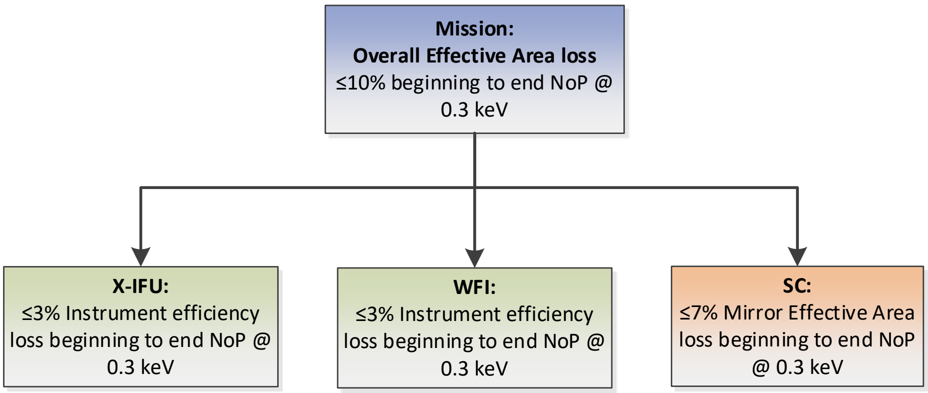

Figure 18: Overall Effective Area calibration decomposition

9 FIELD OF VIEW

9.1 MRD Requirement

Requirement
The ATHENA Mission shall perform Narrow Field observations with a Field of View of 5' diameter.
The ATHENA Mission shall perform Wide Field observations with a Field of View of 40' diameter.
The ATHENA Mission shall perform Fast Chip observations with a Field of View of TBD diameter.

9.2 Decomposition

Using the angle of view formula:

$$\alpha = 2atan\left(\frac{d}{2F}\right)$$

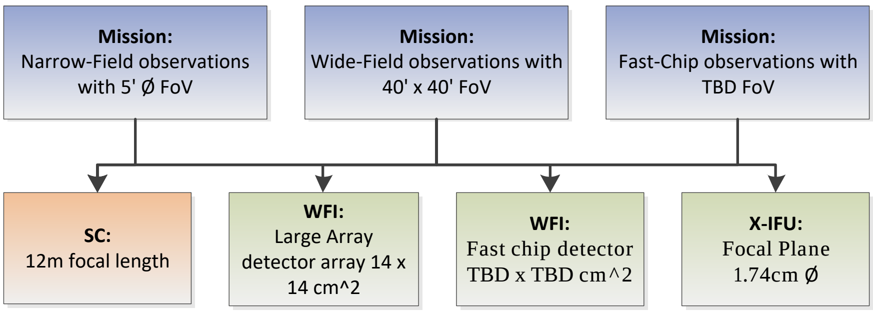

Figure 19: Field of view decomposition

10 TOO REACTION TIME

Note: Please refer to [RD08] for the model which controls this decomposition.

10.1 MRD Requirements

See the MRD.

Note: There is currently a mismatch between the SciRD requirement which effectively specifies: $P(T_r \leq 4\, hours, T_o \geq 50ks) = 0.8$, *and the MRD. This still needs to be resolved with the ASST.*

10.2 Decomposition

The requirement on ToO reaction time is understood to consider the time starting from receipt of an un-validated ToO-alert by the SGS, until the subsequent commencement of TYPE_1 (Narrow-Field) observations of the ToO. The main anticipated steps followed in processing the un-validated ToO-alert are defined in [RD08]. The requirement is interpreted as stating that the CDF(P) of the bivariate distribution of response and observing times shall meet the required performance, e.g. for the GRB-ToO requirement case:

$$\mathrm{P}(\mathrm{T_r} \leq 4\ \mathrm{hours}, \mathrm{T_o} \geq 50\mathrm{ks}) = 0.67$$

10.3 Derived Requirements

On the basis of the analysis described in [RD08], the GRB-ToO requirement has been decomposed to the following tier-1 items in the Product Tree [RD03] as follows.

With the replacement of Malargue with Kourou as an uplink GS, the allocations for the GRB-ToO requirement are now just sufficient (i.e. the model shows the requirement is met).

Note: depending on the observing plan, # of pointings etc., a faster SC agility may be required to be compliant with the SC availability requirement defined in §3 – this will be derived by the Prime as part of the Operational Availability budget.

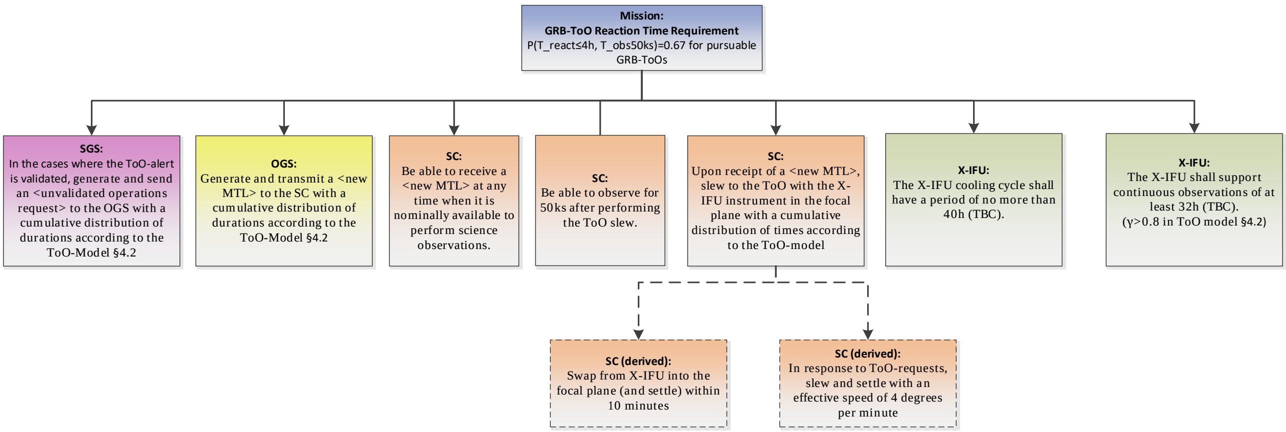

Figure 20: GRB-ToO response time requirement decomposition

11 SCIENCE TELEMETRY LATENCY

11.1 MRD Requirement

See the MRD.

Note: there is a mismatch currently between the SciRD QLA requirement (≤1 day latency) and the MRD (≤2 days latency) which needs to be discussed with the ASST. ≤1 day is not possible with the current GS-contact scheme (1 per day).

11.2 Decomposition

The requirements on latency are divided among the PL, SC, OGS and SGS.

11.3 Derived Requirements

The latency requirements have been broken to the following tier-1 items in the Product Tree [RD03].

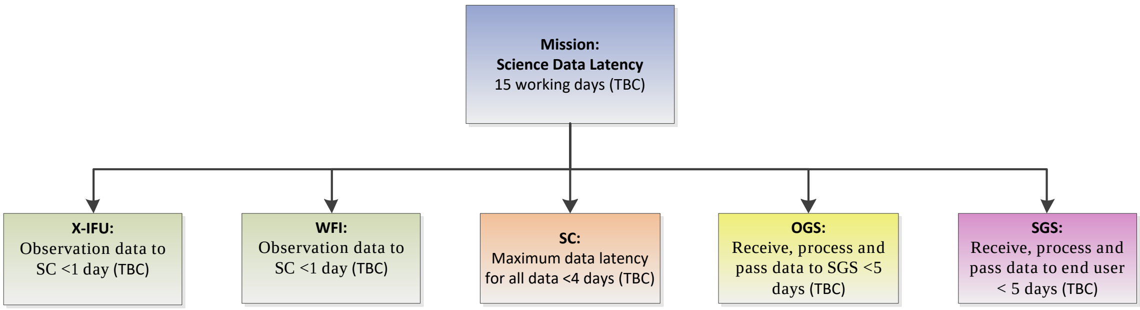

Figure 21: Science data latency requirement decomposition

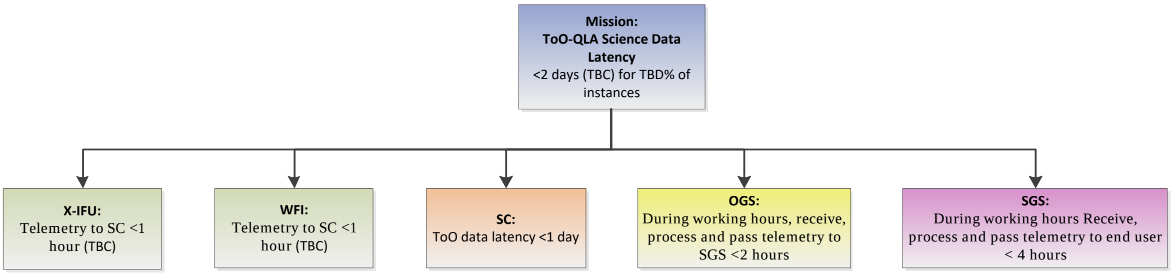

Figure 22: ToO-QLA science data latency requirement decomposition

12 ABSOLUTE TIME ACCURACY

12.1 MRD Requirement

Requirement
The ATHENA Mission shall perform all observations with an absolute photon timing accuracy of ≤50 μs.

12.2 Decomposition

The proposed scheme described is derived from experience of the Integral and XMM-Newton satellites, as described in [RD13], [RD14], [RD15].

12.3 Overview

Time correlation is the process of accurately establishing the relationship between a local time system and a reference time system in order to allow the unequivocal referencing of event arrival times. On a satellite observatory the local time system is commonly known as on-board time (OBT) and the global reference system is the Universal Time Co-ordinated (UTC). All events occurring on-board must be referenced to the OBT time system. The OBT local time system is typically maintained by a crystal oscillator (of TBD MHz) located in a Central Data Management Unit (CDMU).

The OBT is initialised at CDMU switch on and continues to run freely from that point. To ensure oscillator stability, the oscillator temperature is normally maintained above local ambient temperature with a constant heat supply, while feedback control of the oscillator environment or frequency might also be enabled. The OBT can be coordinated between on-board subsystems by the CDMU by means of a periodic broadcast pulse on the SC data bus, typically at 1 second period.

All other spacecraft subsystems then may maintain a local copy of the OBT and use this information for timing of internal events. Subsystems will be required to have their local copy synchronised to the CDMU OBT when they are switched on and to maintain synchronisation through the broadcast pulses. CCSDS standards apply to time codes and typically define the word lengths for seconds and fractions of seconds.

12.4 XMM-Newton Experience

In the case of XMM-Newton a packetized telemetry stream is operated, where packets from the various subsystems are encapsulated by the CDMU in frames of fixed size. The instant of transmission of the first bit of every 16th frame was time stamped on board in the local OBT system, by means of a hardware mechanism that latched and stored on-board the OBT at the right moment.

Each GS operates in UTC and is synchronised through a combination of a local oscillator and a GPS clock. On the ground the GS adds an Earth Received Time stamp (ERT, in the UTC reference system) to the first bit of each frame it receives. As the time between the transmission and the reception of the frame is known within a certain accuracy it is possible to correlate the occurrence of the two specific events in the two time references systems. To correlate the OBT to UTC it is sufficient to subtract from the ERT the signal travel time from the satellite to the GS. This time of flight is calculated in real-time by the mission control system at ESOC from knowledge of the predicted orbital position and the GS location.

Additionally, the CDMU and GS timing systems are not infinitely fast and therefore fixed offsets and delays from these components are also considered, based on calibrations made on-ground. To obtain UTC for any OBT it is necessary to fit the pairs of OBT/UTC with a function and use this function to derive the UTC. If there are variations in the OBT oscillator frequency a non-linear fit is required to achieve accurate timing conversion from OBT to UTC over the period of a typical observation.

The XMM Mission Control System (MCS) uses orbit prediction to calculate the signal travel time from SC to GS. This file, which is distributed with the ODF, is currently updated every revolution shortly after perigee and thus represents a very good prediction of the forthcoming orbit. The ODF also includes an orbit file that is produced after completion of the relevant revolution and is known as the reconstructed orbit file because the data are reconstructed from the continuous ranging measurements that are made from the GS to the SC throughout the revolution. The difference in the time correlation products as calculated from the orbit prediction are generally the same as those from the reconstructed orbit file, to an accuracy of 30µs [RD18]. It should be noted that following any anomaly, for example Emergency Safe Attitude Mode (ESAM), there may have been unforeseen changes to the orbit that reduce the accuracy of the prediction. Therefore, observers must use the reconstructed orbit file for their final analysis.

The SC position is measured by a differential correction technique involving an orbital model that takes into account the Earth potential, the gravitational effects of the Sun and of the Moon, the effect of the Solar radiation pressure, and the momentum control manoeuvre data. This model is constrained with ranging and Doppler measurement data providing line of sight position and velocity that are regularly collected when the satellite is visible over the ground station. The accuracy for orbit reconstruction for the eccentric orbit is normally better than 10 meters along the line of sight.

The relationship between OBT and UTC is not linear, as the crystal oscillator is susceptible to ageing and drift. Over time it has been possible to accurately measure the oscillator performance on both short and long time scales.

12.5 INTEGRAL Experience

The *INTEGRAL* data analysis uses essentially three time systems:

1. The Earth Reception Time (ERT), expressed in coordinated Universal Time (UTC), is defined at the reception of every telemetry frame by the GS. The ERT is determined by atomic clocks located within each of the ground stations used by the mission. The ground stations are synchronized using the GPS.
2. The Terrestrial Time (TT) is used to time tag, on-ground, products and physical events recorded within the instruments. The terrestrial time follows precisely the Atomic International Time (TAI) and does not suffer from leap seconds. In the data products terrestrial times are always formatted as double precision real in unit of *INTEGRAL*

Julian Date (IJD), defined as the number of days since the 1st of January 2000 at 0h 0m 0s (TT) (IJD=JD−2451544.5).

3. The On Board Time (OBT) is defined by counting the number of pulses of an oscillator on board the spacecraft. All on board times are represented as 64 bit integers with a unit of 2^{-20} OBT second even if they are less precise in the telemetry.

The *INTEGRAL* time correlation is the relation between IJD and the OBT. It is derived from measurements, in OBT, of the time at which specific telemetry frames leave the spacecraft (more specifically the leading edge of the first frame bit). OBT measurements are then correlated to the ERT of the corresponding frames. Corrections for on board delays, delays within each of the ground stations and light travel time are taken into account.

The on board delays were calculated and calibrated on ground. Unfortunately, at the beginning of the mission, the on board delay was taken into account with a wrong sign in the time correlation software with the net effect that any IJD derived from an OBT had to be corrected by a positive offset.

The delays between the actual event times and the instrument OBT time tags were measured on ground before the launch. These delays were also derived from flight data using contemporary *INTEGRAL* and *RXTE* observations of the Crab pulsar [RD19]. For all *INTEGRAL* instruments and *RXTE*, the differences in arrival times of the first (main) Crab peak in the pulse profile in radio and X-rays have been measured. The differences between the *INTEGRAL* and *RXTE* measurements, (both using the same ground station), of the X-ray - radio delay is a measure of the instrumental delays, taking *RXTE* as the standard. For *RXTE* an X-ray - radio delay of 268 ± 30 µsec was determined.

12.6 Crab calibration

Calibration of absolute timing has concentrated primarily on the Crab pulsar (PSR B0531+21) because radio ephemerides are provided monthly by the Jodrell Bank Observatory. However, the reference to radio timing limits us to the accuracy of the radio ephemerides. The Crab has been one of the best-studied objects in the sky and it remains one of the brightest X-ray sources regularly observed.

As a standard candle for instrument calibration, the 33ms Crab pulsar has been repeatedly studied (monitored) by many astronomy missions in almost every energy band of the electromagnetic spectrum. In the X-ray regime its pulse profile exhibits a double-peaked structure with a phase separation of 0.4 between the first (main) and the second peak. Measurements of X-ray to radio delays between the arrival times of the main pulse in each energy range of the Crab pulsar have been reported using all high-energy instruments on-board INTEGRAL [RD17] and RXTE [RD18]. The time delays were determined to be 280 ±40 µs and 344 ±40 µs, respectively.

The relative timing accuracy may be defined as the difference between the period measured with the X-ray observatory and the period measured at radio wavelengths evaluated at the epoch of the X-ray observations.

The period of the Crab pulsar in X-rays is typically determined using the publicly available epoch-folding software XRONOS. The closest available Jodrell Bank Monthly radio ephemeris [RD19] before and after the X-ray observation are used to interpolate the radio period P for the time of the first X-ray event of the X-ray observation and the interpolated radio periods used as an initial trial value for the epoch folding. The period derivative P' provided by Jodrell Bank needs to be taken into account when folding the X-ray data.

The ephemeris (epoch, P, P', P'') of the nearest radio observation from the Jodrell Bank can be used as a reference to obtain the phase shift between the time of arrival of the main peak in the X-ray profile and the time of arrival of the main peak in the radio profile to give the *absolute* timing accuracy, via the phase shift multiplied by the corresponding X-ray period found during the relative timing analysis, The Crab pulsar shows a shift of –300μs between the peak of the first X-ray pulse with respect to the radio in the results of various missions. Differences in the shifts observed over several decades in energy are marginal with an average value. Error bars quoted for the different X-ray missions have included systematic errors from the radio measurements.

The origin of the electromagnetic radiation emitted from pulsars is still unclear. Several models have been proposed to explain the origin of the high-energy radiation based on different regions of acceleration in the pulsar magnetosphere, such as the polar cap, the slot gap, and the outer gap models. The radio emission model is an empirical one and the radiation is usually assumed to come from a core beam centred on the magnetic axis and one or more hollow cones surrounding the core The estimated average delay between the emission from differing wavelengths is therefore significant and the site of radio production is distinctly different from that of the X-ray emission. The time delay of about 300μs most naturally implies that emission regions differ in position by about 90 km between radio and X-rays energy bands in a simplistic geometrical model - neglecting any relativistic effects - with the radio emitted from closer to the surface of the neutron star. By implication the delay for a given X-ray energy band depends on average distance of region producing the bulk of photons in that band.

Scatter due to uncertainties in the time correlation process may eventually dominate over measurement of the phase of the main peak which by centroiding can be measured with an accuracy of ~μs.

12.7 Additional Considerations for ATHENA

While the XMM-Newton and INTEGRAL experience indicates the required ATHENA timing accuracy should be attainable, it should be borne in mind there are significant differences in ATHENA implementation to be considered:

- Orbit – L2 at a radial distance ~1.5 10^6 km compared with a HEO orbit of ~10^4 to 10^5 km, implying perturbations and their timescales will be very different, and the greater distance will impact ranging capability
- Use of telemetry packets scheme may be modified by latest CCDS standards, CFTP transmission etc., and the adoption of on-board data distribution techniques (*Spacewire*) 'may render the current approaches obsolete (but hopefully improved)
- Ground contact is not anticipated to be continuous, therefore a daily contact period (e.g. ~3 hours) must be assessed for ranging capability, orbit reconstruction accuracy and propagation etc. Additionally, the nominal use of a single ground station must be examined for potential systematic errors using a single reference time system for ERT.

If anticipated interpolation of ranging would lead to excessive uncertainty, then additional ranging activities will have to be considered as part of operations

- ToO and other observational programmes may require specific timing capability. Also the disruption in planning sequences, pointing modifications etc. would affect the predicted orbital elements and possibly the subsequent data analysis (*especially the QLA*), unless the ranging and time referencing activities also were re-planned and updated.

12.7.1 Error Distribution

Upper limits for the time allocation processes can be estimated, for example using the values reported by [RD13]. They estimated the following:

- The SC clock error to be ~11 μs: Revisit how the ATHENA clock can be improved
- The uncertainty in ground-station delays to be ~5 μs: Revisit with ESOC based on set of GS to be used in 2028
- The interpolation errors to be ~10 μs: Review the effect of more sparse data set
- The error between latching observing time and the start of frame transmission as ~9 μs: Review the OBDH concept for ATHENA
- The uncertainties in the spacecraft orbit ephemeris to be ~30 μs: Check with ESOC what has been achieved with Herschel and GAIA

All these error sources will be random. The resulting scatter can then be considered to be the minimum significant time separation between two arrival times to be considered independent.

12.8 Proposed ATHENA error decomposition

Total PL error	**5 μs**
SC Maximum drift in OBT between consecutive correlation references	5 μs
SC Maximum error in OBT distribution to instrument subsystems	5 μs
SC Maximum error in copying OBT to data transmission	5 μs
Total SC error	**15μs**
OGS Maximum error due to orbital uncertainties (1.5 km)	5 μs
OGS Maximum uncertainty in ground station delay	5 μs
Total OGS Error	**10μs**
SGS Maximum interpolation errors	20 μs
Total SGS error	**20μs**
Total Absolute Time Accuracy (additive)	50 μs

12.9 Derived Requirements

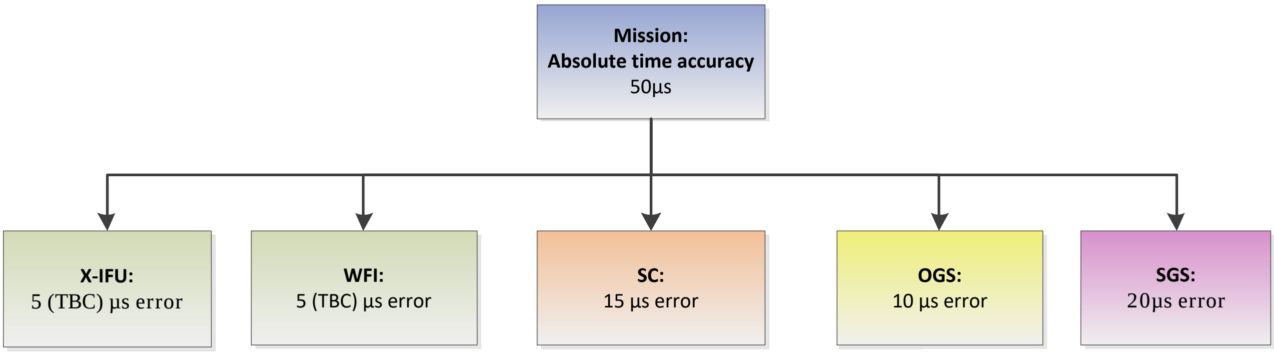

Figure 23: Absolute time accuracy requirement decomposition

13 BACKGROUND

Note: The Background Working Group is responsible for this decomposition, relying on simulations performed using the tool developed under the AREMBES activity [C204-110EE].

13.1 MRD Requirement

See the MRD.

13.2 Decomposition

The level-2 SciRD background requirements for the X-IFU and WFI background are reproduced in the MRD, for x-ray and non x-ray components. To decompose these requirements we use an additional background component classification on the basis of origin, as follows:

- Concentrated: passing through the mirror (note: not necessarily focused)
- Omni-directional: not passing through the mirror.

The following decomposition is made based on an allocation performed by the BWG.

13.2.1 Non x-ray background

The overall requirement at the focal plane is passed to the PL entirely, with the expectation that the PL-teams will evaluate the background-compliance. For counter-part requirements applicable to the SC the total flux requirement in each case is divided into:

1. The omni-directional component, SC requirements for which are TBD as they will depend on the PL-design, AC-effectiveness etc. It is anticipated that these requirements will be generated by the PL-teams in due course and applied to the SC.
2. The component passing through the mirror (allocated as one order-of-magnitude less than the omni-directional component) for which the charged particle diverters are employed. Note that there is uncertainty in the transfer-function of the mirror (being addressed in [T204-117EE: Charged Particle Scattering in Optics (EXACRAD] TDA), and the requirement is not easy to verify as it is expressed. Accordingly, equivalent engineering requirements on the function of the diverters (worst-case proton diversion at specified energies) have been derived by the BWG, and these are the ones being used to drive the diverter design.

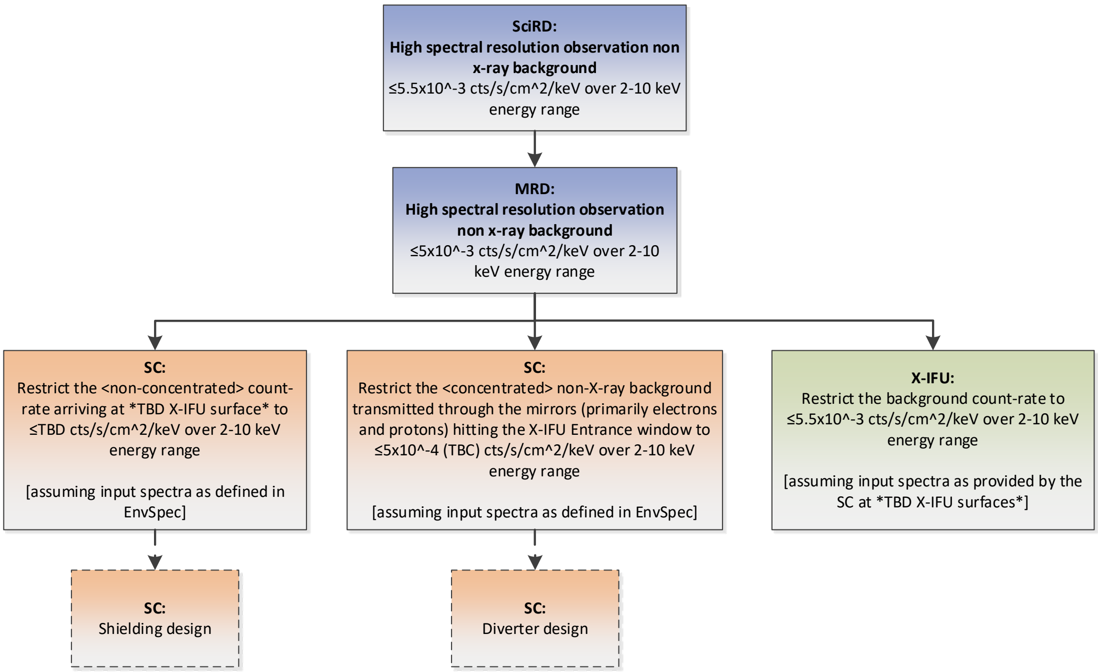

Figure 24: High spectral resolution non x-ray background requirement decomposition

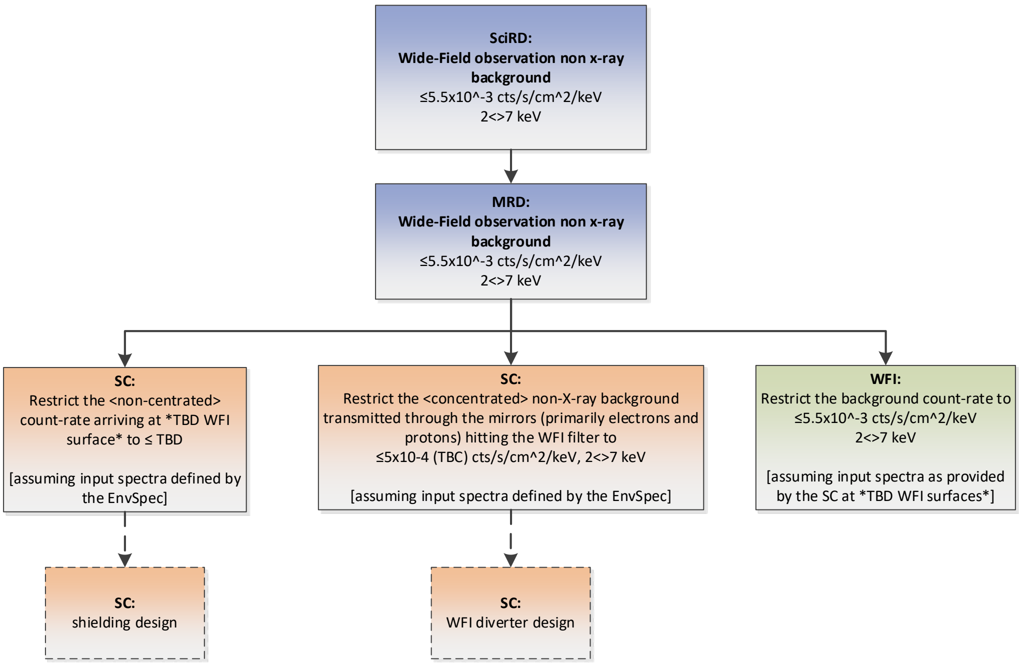

Figure 25: Wide field resolution non x-ray background requirement decomposition

13.2.2 X-ray background

The overall requirement at the focal plane is passed to the PL entirely, with the expectation that the PL-teams will evaluate the background-compliance. For counter-part requirements applicable to the SC the total flux requirement in each case is divided into:

1. The component passing through the mirror due to single and back-reflections in the optics, and which consumes the bulk (>90% for both PLs) of the overall requirement. *Note: the x-ray background requirements related to the mirror design are a function of MM-design and so are currently not under SC Prime responsibility (i.e. does not require evaluation by the SC Prime, but will be evaluated by BWG and Symposium activities). However the SC is required to prevent x-ray background arriving at the focal planes via the interstitial gaps in the MA (i.e. not through pores).*
2. The omni-directional component, which is normalised to a 'per steradian' value (i.e. considering the remaining solid angle after the mirror Ω {~0.03 steradians} is removed) which is then used to impose a requirement on the SC FMS-baffling (an identical requirement is in principle applicable to the PLs, but this is not separately required, being part of the overall requirement passed entirely to the PL).

Note that, for [2], considering a simplified geometric assessment of the share of solid-angle between the Mirror, SC and PL for the WFI instrument (see the following figure – this envelopes the X-IFU case), it is apparent that the SC FMS-baffling system will cover only ~5% of the sky. Considering further that the omni-directional component of the x-ray background is <10% of the overall requirement, the SC FMS will be addressing only ~0.5% of the requirement.

Parameter	Value
FL [m]	12.00
Ø_mirror [m]	2.40
α_mirror [°]	5.80
baffle height [m]	0.40
FP dimension [m]	0.15
x_1 mirror_edge [m]	1.21
y_1 mirror_edge [m]	11.94
x_2 FP_edge [m]	0.08
y_2 FP_edge [m]	0.00
baffle half_angle [°]	5.44
x_3 baffle edge [m]	0.11
y_3 baffle edge [m]	0.40
x_4 baffle edge [m]	-0.08
y_4 baffle edge [m]	0.00
line equation:	
m	2.13
c	0.16
circle-line intersection	
d_x [m]	0.19
d_y [m]	0.40
d_r [m]	0.44
D	-0.03
x_5 intersection [m]	5.05
y_5 intersection [m]	10.89
Checksum	12.00
Ω_SC [sr]	0.55
Ω_mirror [sr]	0.03
Ω_PL [sr]	11.98
WFI Decomposition	**Value**
WFI x-ray [cts.s-1.cm-2.keV-1]	3.20E-04
Concentrated [cts.s-1.cm-2.keV-1]	3.00E-04
Omni [cts.s-1.cm-2.keV-1]	2.00E-05
Omni [cts.s-1.cm-2.keV-1.sr-1]	***1.60E-06***
Omni_SC [cts.s-1.cm-2.keV-1]	*8.78E-07*
Omni_PL [cts.s-1.cm-2.keV-1]	*1.91E-05*
X-IFU Decomposition	**Value**
X-IFU x-ray [cts.s-1.cm-2.keV-1]	3.80E-03
Concentrated [cts.s-1.cm-2.keV-1]	3.50E-03
Omni [cts.s-1.cm-2.keV-1]	3.00E-04
Omni [cts.s-1.cm-2.keV-1.sr-1]	***2.39E-05***
Omni_SC [cts.s-1.cm-2.keV-1]	*1.32E-05*
Omni_PL [cts.s-1.cm-2.keV-1]	*2.87E-04*

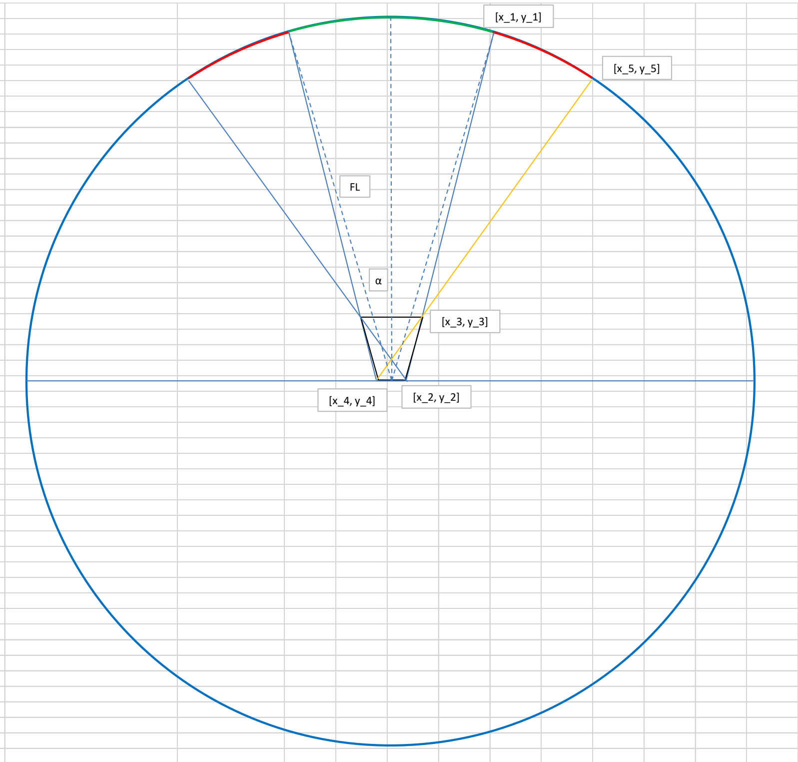

Figure 26: Simplified geometric assessment of distribution of solid angle

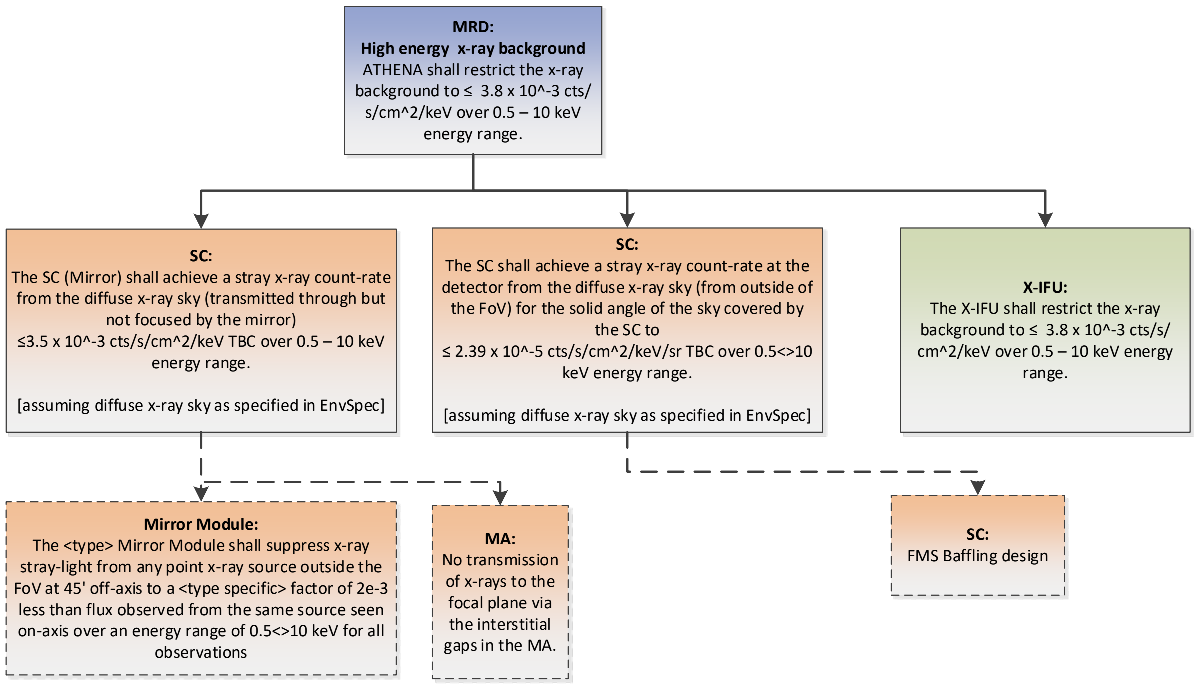

Figure 27: High spectral resolution observation x-ray background requirement decomposition

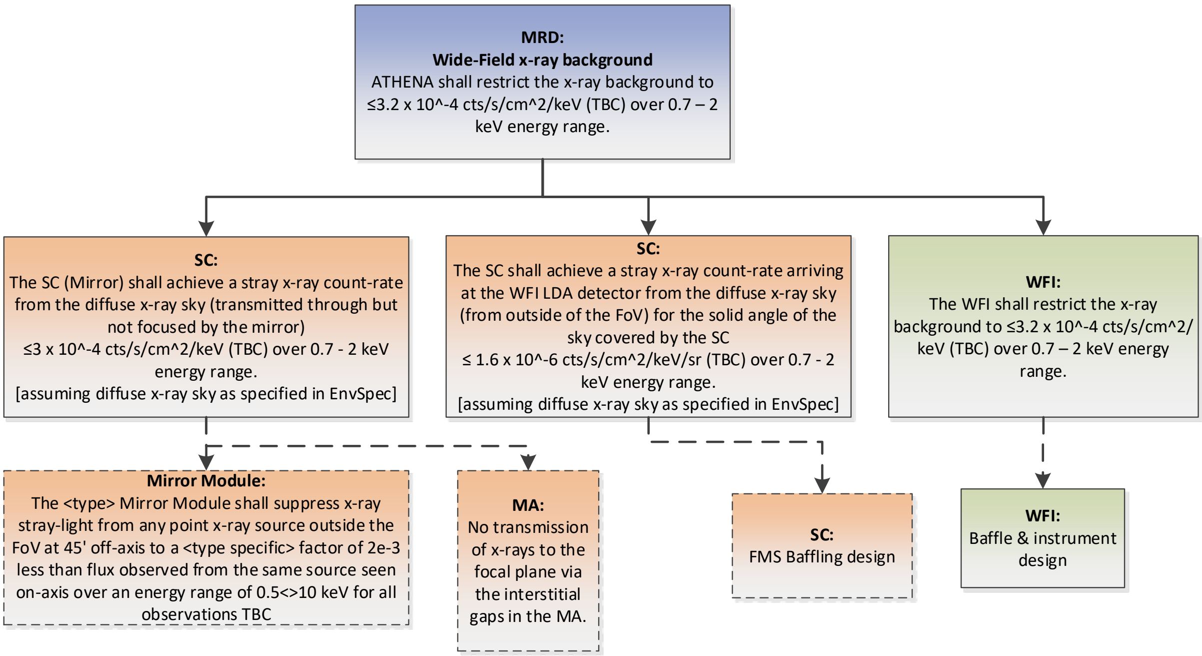

Figure 28: Wide-field observation x-ray background requirement decomposition

14 SC (TELESCOPE) POINTING

14.1 Motivation

This section provides a definition of the pointing requirements for the ATHENA SC, based on the latest requirements specified by the ASST. Note that some pointing requirements are not fully specified and some evolution should be expected. All pointing requirements currently to 95 % CL using a temporal statistical interpretation. Furthermore the definition here has been expanded as a function of each focal plane – this introduces a mismatch with the SciRD (see particularly SCIRD-951) which will need to be clarified in due course.

14.2 Definitions

These performance error requirements are all applicable to the SC (telescope LoS) with respect to the intended target, in an inertial (e.g. J2000) reference frame. To define the telescope LoS we make use of the following definitions:

<Telescope LoS>: The telescope LoS is the vector connecting the nominated <dwell-point> on the focal plane with the <MA nodal point>.

<MA nodal point>: The geometric location in the Mirror Assembly which has the property that rotations around it, to first order, lead to no image motion in the focal plane. The nodal point is located on the optical axis of the MA, on the plane defined by the virtual intersection of the primary and secondary mirrors of the MMs.
<Dwell Point>: The requested location on the focal plane where the target is placed. The 9 requested <dwell points> are indicated as purple circles in the following figure, being:

1. WFI-LDA: (3 locations, repeated in every quadrant)
    a. On-Axis: Centre of LDA (SCI-POI-R-050)
    b. Corner: 3' diagonally off geometric centre of LDA
    c. Centre of one quadrant (~14' off geometric centre of LDA) (SCI-POI-R-051)
2. WFI-FC (centre)
3. X-IFU (centre)

The rationales behind these positions are:

- On-Axis & Corner: It is currently not clear which of these positions is better for the survey. It will depend on the performance of the mirror (e.g., PSF as function of off-axis angle; vignetting; stray light), the choice of dither pattern and the final size of the gaps between the LDs.
- Single LDA: This would be the position of choice for non-survey imaging observations of sources/areas that do not require the full 40'x40' field of view but have extends of <20' diameter, e.g., cluster surface brightness, supernova remnants, stellar associations, etc.

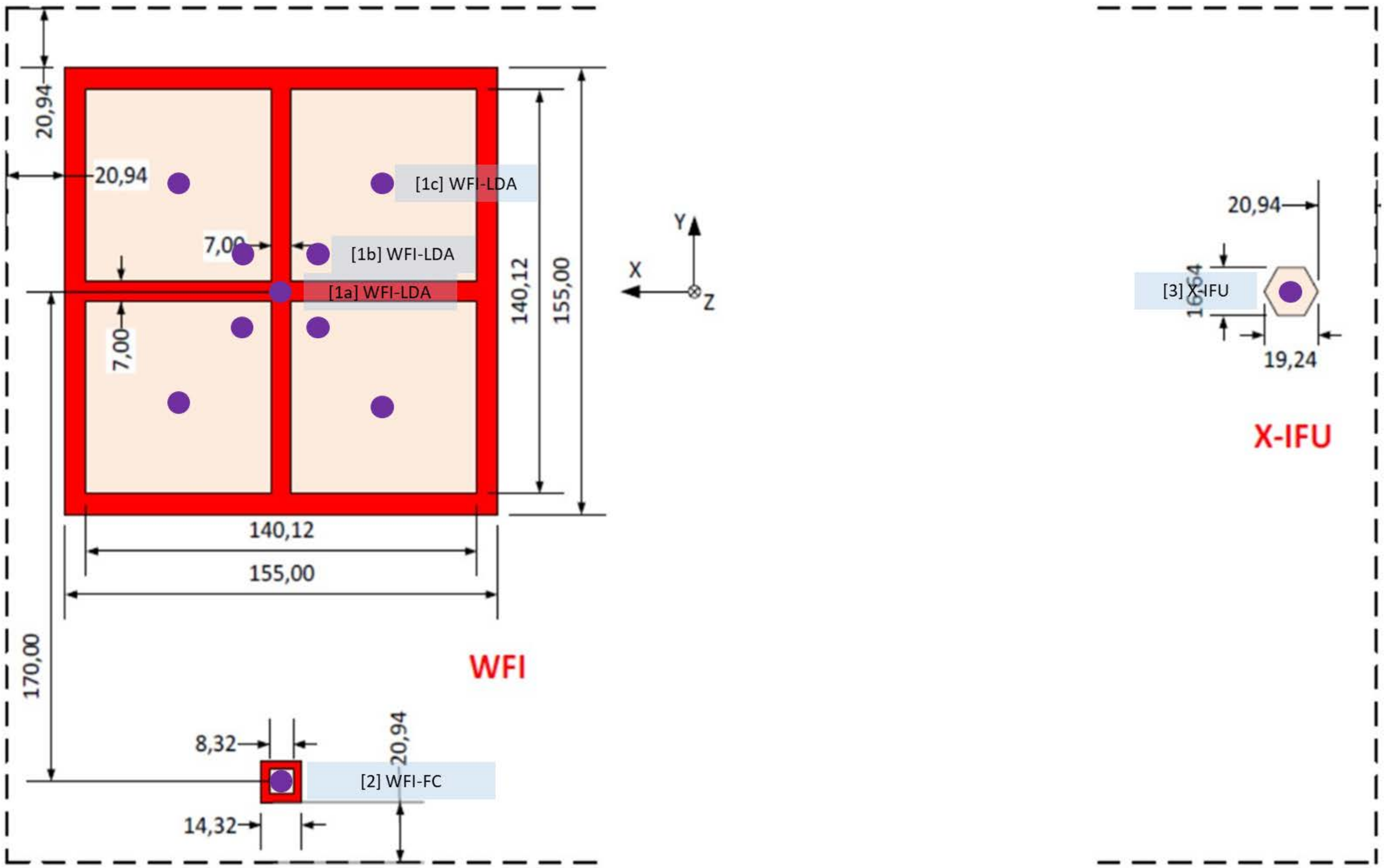

Figure 29: The 11 dwell-points (purple dots) defined for the ATHENA focal planes (note: separation between WFI & X-IFU focal planes is at SC Prime discretion and not to scale in this image)

Table 11: SC LoS pointing requirements summary (table also in SRD)

	X-IFU		WFI - LDA		WFI - FC (defocused)		WFI - FC (window mode)	
	Req. ['']	Comment	Req. ['']	Comment	Req. ['']	Comment	Req. ['']	Comment
AKE	3	Astrometry required for counterpart radio observations, limited scope for ground-improvement	3	Combined with SGS requirement post-process images on ground to 1'' AKE	-	WFI-FC not used for astrometry	-	WFI-FC not used for astrometry
APE	17.2	Previous 7'' requirement was the justification for the core fast array, but this has now been dropped. Detector is 16.64 mm across, so to get a target within an (arbitrary) 1 mm of centre is ~17'' APE for 58µm plate scale	173.0	Justification is to ensure focused 10 keV energy PSF (r=7'') at dwell point <WFI-LDA [2]> does not hit the quadrant boundary	20.0	Boresight source positioning sufficient accurate not to contribute to the uncertainty in the effective area calibration (due to vignetting effect) ≥1%.	28.8	Justification is to ensure focused 10 keV energy PSF (r=7'') does not hit the window boundary (window is 32 x 64 pixel strip across centre of FC)
PDE	4	Raster scan to disentangle pixel effects	-	No Raster foreseen	-	No Raster foreseen (de-focused PSF over large # pixels)	-	-
RKE	TBD	Derived from SC Prime HEW budget (so not in SRD)	TBD	Derived from SC Prime HEW budget (so not in SRD)	TBD	Derived from SC Prime HEW budget (so not in SRD)	TBD	Derived from SC Prime HEW budget (so not in SRD)

14.3 Absolute Knowledge Error (AKE)

14.3.1 MRD Requirement

Requirement
The ATHENA Mission shall achieve a reconstructed Astrometric error of <3'' to 95% confidence level (TBC) for all observations. The ATHENA Mission should achieve a reconstructed Astrometric error of <0.66'' to 95% confidence level for Wide-Field observations.

Note: This was relaxed by the ASST to 4.5'' @ 99.7% confidence in the SciRD, since this is difficult to achieve, particularly with the X-IFU where the improvement from ground-based processing is less (than the factor 3-4 realised by XMM Newton) due to the lack of multiple stars in the image. Taking the centroid of the primary stellar source may allow some improvements to the AKE, but this is yet to be quantified.

Considered applicable to: WFI-LDA, X-IFU.

14.3.2 Decomposition

This is the astrometry requirement for a posteriori knowledge of the angular position of an observed object in the sky, and is flown to the SC LoS AKE (applicable on-board) and a corresponding improvement factor (WFI-only) applicable to the SGS.

14.3.3 Derived Requirements

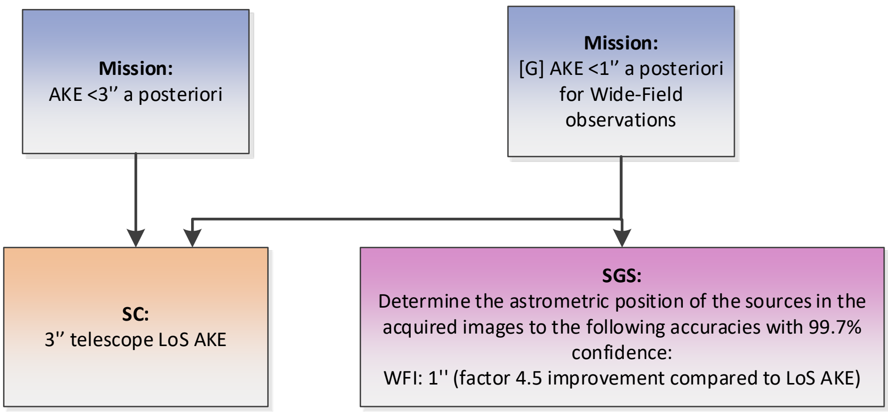

Figure 30: AKE decomposition

14.4 Absolute Performance Error (APE)

Note: the following derivations do not preclude a tighter APE requirement being derived by the SC from the A_eff requirements (i.e. to suppress vignetting at the target, see §7).

14.4.1 SciRD Requirements

SCIRD-951 is defined for the X-IFU fast core-sensor, but this is now redundant.

14.4.2 Derivation

See Table 11.

14.4.3 Derived Requirements

As per Table 11.

14.5 Pointing Drift Error (PDE)

14.5.1 SciRD/ConOps Requirement

SCIRD-949.

It is envisaged that ATHENA shall be able to perform dithering to disentangle detector effects from true features in the observed objects for the X-IFU instrument. Typical long observations, used to observe weak sources, will be split into different pointings. As a minimum a Raster scan with 9 observations centred on the target under observation and separated by 3 pixels is anticipated.

The Raster Mode of Pointing shall be an optional mode for pointing to be used for any observation of duration longer than T_long seconds (T_long shall be a configurable parameter and typically >30ks.) The mode shall comprise a series of exposures of equal duration (T_exp) separated by small slews in order that the telescope axis moves in a raster pattern centered around a given sky direction. The raster coverage shall comprise N lines each of M pointings, with d the angular distance between successive lines and successive steps within one line. N, M and d shall be configurable parameters. The typical Values are M=N=3 and d = 13'' (3 x pixels). T_exp is expected to be ~2.5ks under the current assumption for the time taken to move between raster pointings. Then T_long ~ N*M*T_exp.

14.5.2 Decomposition

If a previous raster-point hold encountered a 4'' drift to the left, and the current raster point also drifts 4'' to the right, there is still no overlap in the 5'' diameter HEW due to 3 pixels (13'') spacing of points (4+4+5=13).

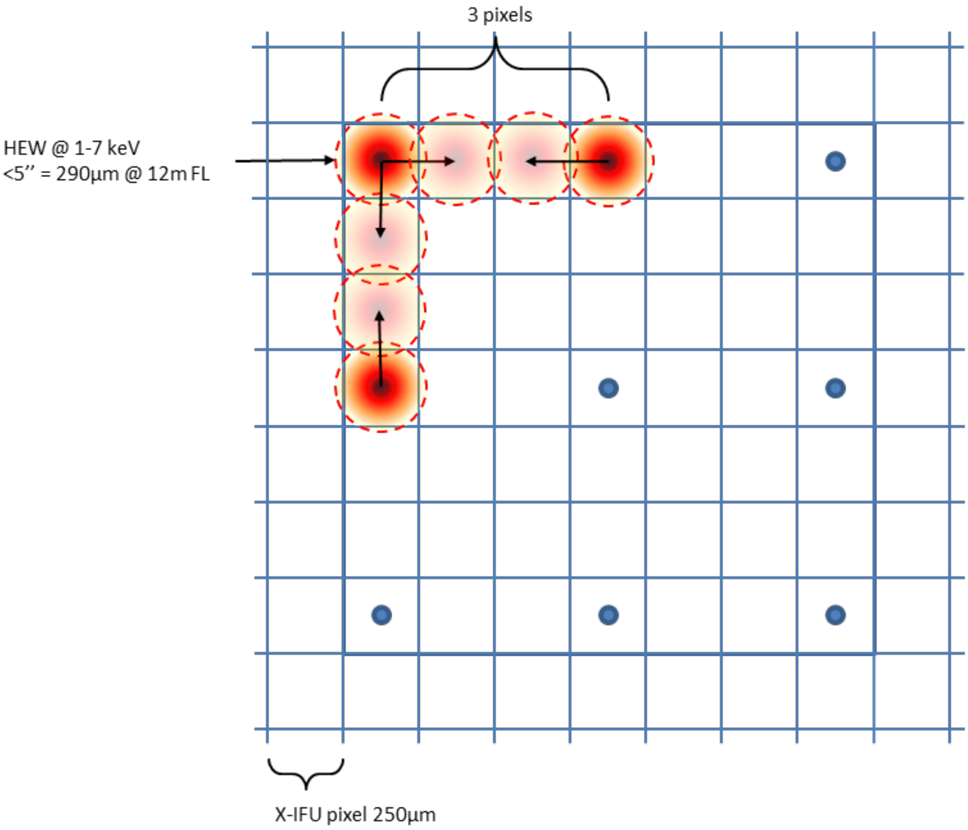

Figure 31: PDE requirement driven by X-IFU reference raster scan

14.5.3 Derived Requirements

A PDE of 4'' x, y over the typical exposure time (T_exp=2.5ks) is therefore defined for the 3x3 Raster scan case described above. Longer exposures up to the 100ks requirement are assumed to be split into larger (larger values of N and M) or repeated scans such that the associated duration is unchanged.

Note: if the step size between nominal scan locations is enlarged, the requirement becomes looser.

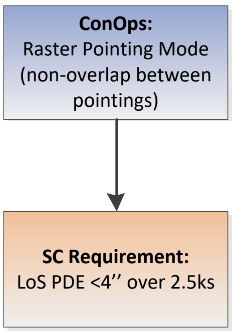

Figure 32: Raster Pointing Mode decomposition to PDE

14.6 HEW Budget (RKE example – part of SC budgets)

14.6.1 MRD Requirements

The HEW requirements are all intended 'on ground' i.e. after best knowledge correction of the direction from which the photons were received. Note that without any attitude sensors or telescope bore-sight calibration (using imagery during science or from regular calibration campaigns) this would simply be the pointing Performance Error of the telescope. The HEW is broken down into several components, e.g.:

- Mirror module internal errors
- Mirror assembly errors (alignment, tilt, focus, structure thermal deformation)
- De-focus due to deviation from nominal focal length
- Relative Knowledge Error (RKE) of Telescope LoS.

The relevant time window for the HEW (image quality) is the image acquisition duration. All errors with frequencies above this time scale will affect the HEW. Corrections of photon positions at these frequencies, using attitude knowledge or centroid measurements from the image, may reduce the HEW but the corrections will still be affected by estimation errors. The worst case time window is defined as Δt, being the longest observation period, up to 100ks. Knowledge errors longer than this time scale will not affect the image quality / HEW.

Note that for most science targets the telescope bore-sight calibration (offset from star tracker frame) can actually be done using centroiding of identified sources in the science image itself to properly superimpose data accumulated during an observation (could be split into segments with regular computation of the centroid correction). This has been mentioned as a strategy and the achievable accuracy is summarized in the picture below (from 'Athena Source Centroiding' memo):

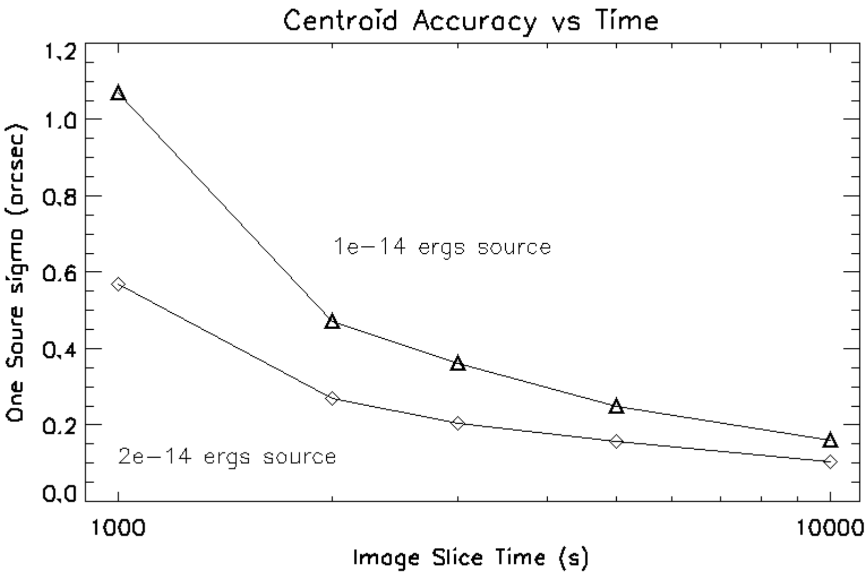

Figure 33: Centroid accuracy vs time for 2 sources with different brightness

The data in the figure above are for one source only. With multiple sources the reduction in systematic errors for pathological source locations and rotations should further improve calibration accuracy.

There is a trade-off to be made between which error frequency band should be addressed by centroiding or AOCS and which band should be addressed by constraining thermos-elastic deformations. With this concept, the RKE requirement on the telescope LoS can be allocated to three sub-contributors:

- Centroiding residual errors from timescales of 100ks to 2ks
    - Error in calibration algorithm and hardware limitations (perhaps of order 1 arcsec, limited by pixel size and calibration technique)
- Relative knowledge error of the LoS from timescales of 2ks to the Nyquist frequency of the star tracker (≈5Hz)
    - Thermoelastic deviation in the star tracker to telescope alignment (between centroiding corrections)
    - Star tracker error
- Platform jitter above the Nyquist frequency of STR frequency
    - e.g. microvibrations, due to the reaction wheels or cryo-coolers.

This is illustrated below in a conceptual power spectral density diagram:

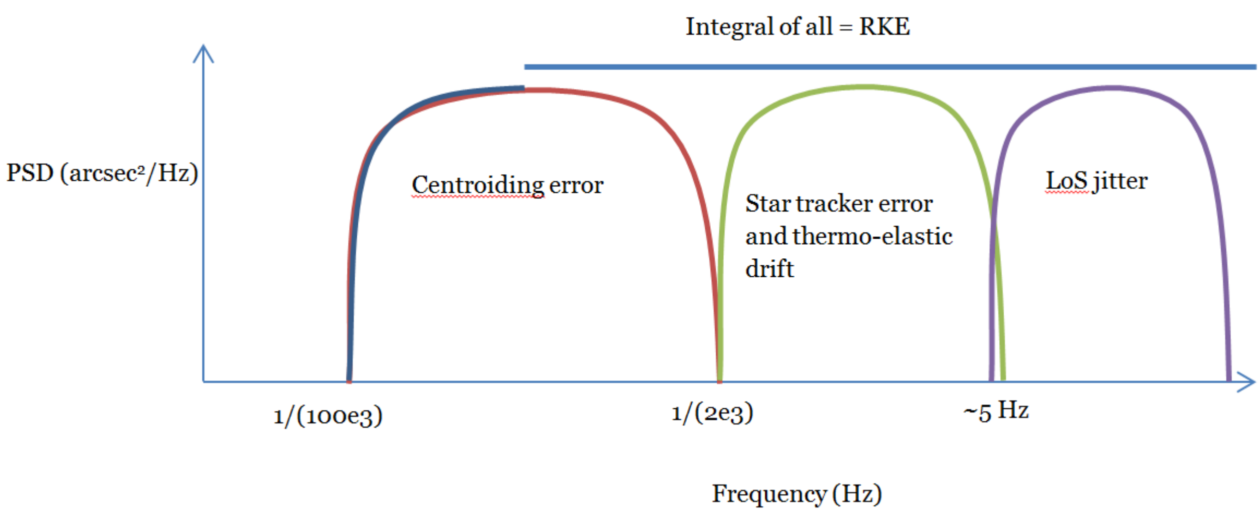

Figure 34: conceptual PSD for RKE allocation to 3 sub-contributors

14.6.2 Relative Knowledge Error (RKE)

Note: The RKE is a contributor to, and therefore derived from, the image quality (HEW) requirement, which is entirely passed to the SC (i.e. it is a SC budget). Consequently, it is anticipated that the RKE requirement shall be derived by the SC Prime, and several routes to satisfying the HEW requirement can be envisaged, with differing consequences for the RKE requirements imposed on the SC (e.g. using an active-focusing mechanism).

14.6.2.1 Defining RKE

A requirement on the "Knowledge Error of Telescope LoS (above frequency f)" can be written in ESA standards language as: "The Relative Knowledge Error (RKE) of each telescope's pointing for targets across the entire field of view [only if applicable] over a duration of TBD s shall be less than TBD arcsec at TBD % confidence, using the temporal statistical interpretation."

The RKE refers to the difference in absolute knowledge error (AKE) and mean knowledge error (MKE) over a specified time window Δt (see ECSS-E-ST-60-10C); RKE = AKE – MKE = Absolute Knowledge Error – Mean Knowledge Error (over period t). The temporal statistical interpretation means that it shall meet the requirement TBD % of the time.

14.6.2.2 Using RKE

The reason to define a Relative Knowledge Error (RKE) instead of an Absolute Knowledge Error (AKE) is because to get a low HEW and hence a high quality image the Mean Knowledge Error (MKE) over the duration that the photons were accumulated is not important.

This means that some photons could be collected at the beginning of the observation time window Δt and the end of the window and they could be superimposed to form an image with low HEW as long as (ignoring other HEW contributors) the knowledge error of the telescope LoS over all frequencies > $1/(\Delta t)$ is properly constrained by an RKE requirement. If during the entire observation there was a constant LoS knowledge error of 1 arcmin (for example) it doesn't affect the quality of the image, since all photons in this accumulated image will share this same bias in the correction of their positions using the star tracker data.

14.6.2.3 Confidence level of the requirement

In order to comply with the HEW budget, the LoS shall collect 50% of the photons from point source within the required circle. This translates into a requirement for the LoS being pointed for 50% of the time to the target point source.

The requirement therefore shall have temporal statistical interpretation and confidence level of 50%. In order to translate this into a per axis pointing requirement, we assume the error having a bivariate normal distribution (Gaussian in both directions) with same standard deviation in both directions and zero mean. With such an assumption, given the standard deviation sigma, the range within which a point can fall with probability of 50% is equivalent to $\approx 2.35\sigma$. This means that HEW requirement can be interpreted as 2.35σ confidence level.

14.6.3 Derived Requirements

The variation of the knowledge in the time window Δt=100ks of the observation will have a direct impact on the reconstructed photon position (image blurring). In pitch and yaw (RKExy) this will translate directly into a PSF degradation of the same magnitude.

In roll, (RKEz) this will to first order have no effect on the HEW of a source located at the centre of the FoV. However, for objects further out in the FoV, RKEz will have a more pronounced impact. The MRD requirement is to maintain the HEW to 10'' at 25' off-axis, which implies the use of a W-S telescope but does not explicitly take into account blurring effects due to RKE. The contribution HEWz to the PSF for an object 25' from the LoS can be expressed as function of the RKEz, such that:

$$25' \times \tan RPE_z = contribution\ to\ HEW\_z$$

Note: The final FoV of the WFI instrument will determine this mapping. Note that the statistical level shall be scaled to get the correct HEW CL.

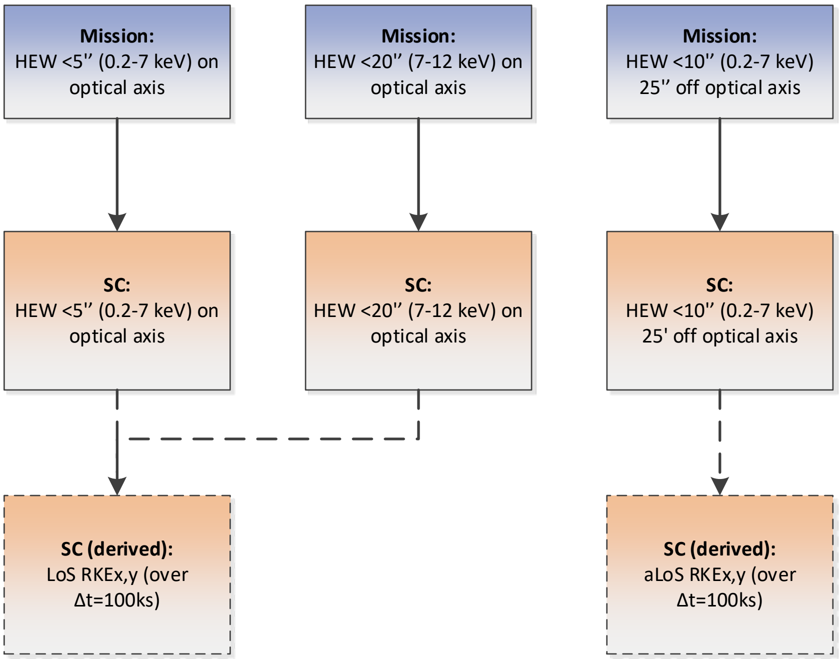

Figure 35: HEW requirements example decomposition

15 DELTA V BUDGET (STATION-KEEPING)

15.1 Motivation

Most line-items in the ΔV budget are defined in the CReMA [RD23], with the exception of the station-keeping and safe-mode ΔV during the operational phases, which must be calculated as a function of the assumed limit on SC noise, the frequency of Safe Mode events, and the mission duration. Furthermore, the margins to be applied are not defined in the CReMA.

15.2 Decomposition

Assuming that manoeuvre accuracy and orbit determination requirements are met, the ΔV budget for the ATHENA SC station-keeping and safe-mode during the operational phases is a function of the SC non-gravitational acceleration standard deviation, the NoP and EoP durations, and the budgeted number of safe-mode events.

Three simulation cases to determine the required yearly station keeping ΔV are reported in the CReMA, corresponding to different assumptions on the SC ECV (for different perturbation environments and predictability of the parasitic ΔV):

- Case 1: Balanced thruster configuration with no residual ΔV caused by attitude manoeuvres. The simulation has therefore little non-gravitational acceleration. Different standard deviation values for the variation of the solar radiation pressure are discussed.
- Case 2: Unbalanced thruster configuration with predictable ΔV. Noise is assumed on the deterministic ΔV.
- Case 3: Unbalanced thruster configuration with arbitrary ΔV (Herschel case).

An additional case simulates the additional ΔV needed for Safe Mode events:

- Case 4: Special event cases as e.g. safe mode or required re-pointing.

Dependant on the proposed SC design and the mission duration, the required ΔV allocation for a nominal mission can be defined from these simulation results. As required by the CReMA, this decomposition uses an extrapolation from a specific noise case value for the station-keeping or Safe-Mode ΔV until the ΔV value for the next case is reached.

- The worst-case 'Maximum ΔV per year' (sub-case #-3 for each case) for each of the cases defined above (the three data points on Figure 36). This corresponds to auto-correlation times for ECV of 1, 5 and 100 days, and 10% standard deviation for the reflectivity coefficient with an auto-correlation time of 100 days. We then multiply by the NoP duration.
- The worst-case 'ΔV per safe mode' (the three data points on Figure 37) assuming an occurrence of the safe mode at the worst case time and with a worst case duration. We then multiply by the NoP duration and number of Safe Mode events per year.

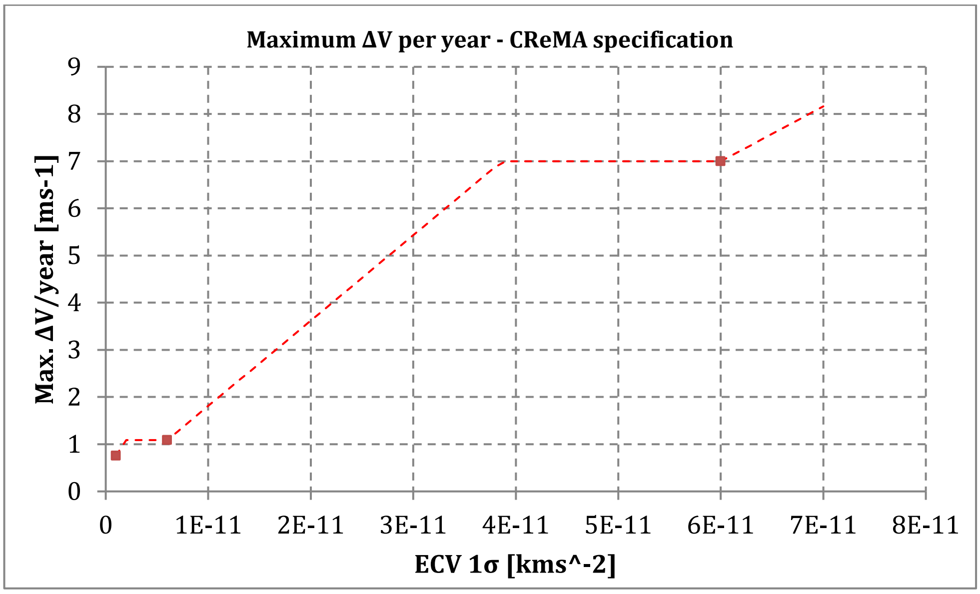

Figure 36: Worst-case maximum ΔV per year

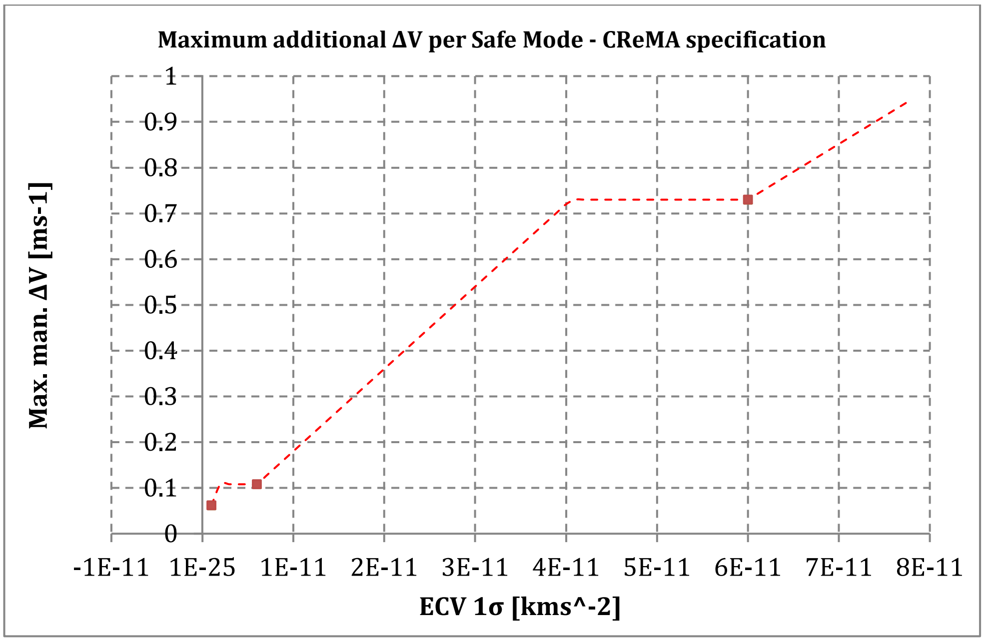

Figure 37: Worst-case additional ΔV per Safe Mode

In addition to the values taken from the CReMA analysis, we define the additional parameters SC system-noise, NoP, EoP durations, and # of Safe-Mode events per year (2).

Table 12: ΔV budget input parameter definition

Parameter	Value
ECV_SC 1σ [km.s^-2]	1.00E-11
Selected Number of Safe Modes [#/year]	2
Nominal Operations Phase Duration [years]	5
Extended Operations Phase Duration [years]	5
ΔV_m1 [m.s^-1]	0.248
ΔV_m2 [m.s^-1]	0.329
ΔV_m3 [m.s^-1]	1.566
ΔV_s1 [m.s^-1]	0.062
ΔV_s2 [m.s^-1]	0.108
ΔV_s3 [m.s^-1]	0.73
ECV_1 [km.s^-2]	1E-12
ECV_2 [km.s^-2]	6E-12
ECV_3 [km.s^-2]	6E-11

$$\Delta V\_SK_{ECV_{SC}} = \begin{cases} \min\left(\frac{ECV_{sc}}{ECV_1}.\Delta V_{m1}, \Delta V_{m2}\right).T_N, & ECV_1 \leq ECV_{SC} < ECV_2 \\ \min\left(\frac{ECV_{sc}}{ECV_2}.\Delta V_{m2}, \Delta V_{m3}\right).T_N, & ECV_2 \leq ECV_{SC} < ECV_3 \\ \left(\frac{ECV_{sc}}{ECV_3}.\Delta V_{m3}\right).T_N, & ECV_3 \leq ECV_{SC} \end{cases}$$

$$\Delta V\_SM_{ECV_{SC}} = \begin{cases} \min\left(\frac{ECV_{sc}}{ECV_1}.\Delta V_{s1}, \Delta V_{s2}\right).SM_{year}.T_N, & ECV_1 \leq ECV_{SC} < ECV_2 \\ \min\left(\frac{ECV_{sc}}{ECV_2}.\Delta V_{s2}, \Delta V_{s3}\right).SM_{year}.T_N, & ECV_2 \leq ECV_{SC} < ECV_3 \\ \left(\frac{ECV_{sc}}{ECV_3}.\Delta V_{s3}\right).SM_{year}.T_N, & ECV_3 \leq ECV_{SC} \end{cases}$$

With similar expressions for the EoP. The selected implementation is to restrict the SC noise standard deviation to $ECV_{SC} = 1e10^{-11} km.s^{-2}$, resulting in the following overall ΔV budget. The margins to be applied in the budget are also specified, along with an additional Operational Contingency allocation.

Note: if the Prime wishes to use a lower SC noise, analysis must be provided to demonstrate that this is achievable.

Table 13: ΔV budget corresponding to ECV_1

Manoeuvre	dV [m.s^-1]	Type	Margin	dV [m.s^-1]
Transfer				
TCM#1 (perigee velocity correction)	12.7	Deterministic	5%	13.335
TCM#1 (LV dispersion correction)	36.3	Stochastic	0%	36.3
TCM#2	2.47	Stochastic	0%	2.47
TCM#3	0.24	Stochastic	0%	0.24
Station-keeping				
Nominal Operations Phase	9.05	Orbit Maintenance	50%	13.575
Extended Operations Phase	9.05	Orbit Maintenance	50%	13.575
Safe-Mode events (NoP)	1.80	Orbit Maintenance	100%	3.6
Safe-Mode events (EoP)	1.80	Orbit Maintenance	100%	3.6
Operational Contingency	10	Stochastic	0%	10
Disposal				
Disposal manoeuvre	10	Stochastic	0%	10
Total	93.41			107

Note: The changes since the previous budget are (i) reinstatement of the full V-P allocation (A-6 development is not pursuing dynamic launcher programmes), and (ii) 50% reduction in margin on operational phase manoeuvres.

15.3 Derived Requirements

The requirement has been broken to the SC as follows:

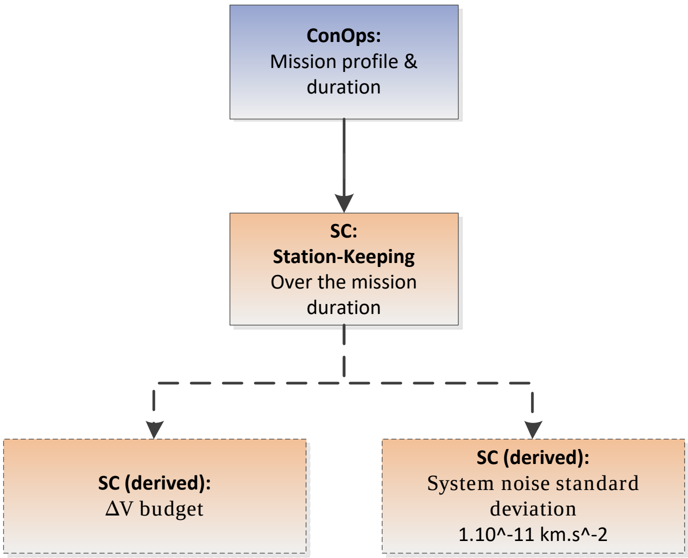

Figure 38: Station-keeping ΔV decomposition