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DOCUMENT

# ATHENA - Concept of Operations

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# 1 REFERENCE DOCUMENTS


[RD 1] ATHENA - Science Requirements Document, ATHENA-ESA-URD-0001, Issue 1.0, 12/06/2014.

[RD 2] ATHENA - Mission Requirements Document, ATHENA-ESA-TRD-0001, Issue 1.0, 12/06/2014.

[RD 3] ATHENA - Mission Budgets Document, ATHENA-ESA-RP-0001, Issue 1.0, 12/06/2014.

[RD 4] ATHENA: The Advanced Telescope for High-Energy Astrophysics. L2 Proposal, Kirpal Nandra et al., 15/04/2014.

[RD 5] ATHENA – Consolidated Report on Mission Analysis, MAS Working Paper no. 598.

[RD 6] ATHENA - Mission Assumptions Document. TBW

[RD 7] ATHENA - Science Operations Assumptions Document. TBW

[RD 8] Call for mission concepts for the Large-size "L2" mission opportunity in ESA's Science Programme.

[RD 9] ATHENA - Payload Definition Document, ATHENA-ESA-PDD-0001, Issue 1.0, 12/06/2014.

[RD 10] Cosmic Vision: Space Science for Europe 2015-2025. BR-247.

[RD 11] Technology Readiness Levels handbook, TEC-SHS/5551/MG/ap, v1.6.

[RD 12] List of ESA Approved Standards (LEAS), ESSB-LEAS, Issue 3.7, rev.2, 09/09/2013.

[RD 13] Space Debris Mitigation for Agency Projects. ESA/ADMIN/IPOL(2008)2, 01/04/2008.

[RD 14] Margins philosophy for science assessment studies. SRE-PA/2011.097, Issue 1.3, 15/06/2013.

[RD 15] ATHENA – Environmental Specification. TBW

[RD 16] NGRM Specification for Assessment Phase. SRE-F/2013.009/SP. Issue 1.1, 15/02/2013.

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[RD 21] ATHENA – Project Management Plan, ATHENA-ESA-PL-0001, Issue 1.0, 12/06/2014.

[RD 22] ATHENA – Risk Policy, Management and Assessment, ATHENA-ESA-POL-0001, Issue 1.0, 12/06/2014.

[RD 23] ATHENA –Baseline Schedule, ATHENA-ESA-SC-0001, Issue 1.2, 12/06/2014.

[RD 24] ATHENA – A6 Mitigation Options, ATHENA-ESA-TN-0001, Issue 1.1

[RD 25] Space engineering: Space segment operability. ECSS-E-ST-70-11C, 31/07/2008.

[RD 26] CDF Study Report: IXO Telescope. CDF-86(A), April 2009.

[RD 27] IXO Consolidated Report on Mission Analysis, MAS Working Paper No. 559, Issue 1.0, 15/09/2010.

[RD 28] ATHENA Internal Study Report see ATHENA: Internal Study Report, SRE-PA/2011.033/NR, 1.0, 22/06/2011]

[RD 29] Space engineering: Radio frequency and modulation, ECSS-E-ST-50-05C, Oct 2011.

[RD 30] IXO Mission Requirements Document, SRE-PAM/2009-MRD/PG, Issue 1.4, 20/09/2010.

[RD 31] IXO Assessment Study: K-band assessment, IXO.TCN.ASU.SAT.00001

[RD 32] IXO Concept Trade-Offs, IXO-TASF-TN-003.

[RD 33] ATHENA - ToO Reaction Architecture Trade Off, ATHENA-ESA-TN-0002, Issue 1.2.

[RD 34] Jacobi-Forbidden return heliocentric trajectory [ref GAIA document: MAS Technical Note No. 93 GAIA: Disposal after End of Life, Issue 1.0, M. Landgraf, May 2013.]

[RD 35] ATHENA - Product Tree, ATHENA-ESA-PT-0001, Issue 1.1, 12/06/2014.

[RD 36] ATHENA – Science Management Plan, TBW

[RD 37] ATHENA – Acronyms and Definitions, ATHENA-ESA-LI-0001, Issue 1.0.

# 2 INTRODUCTION & SCOPE

This document is an instance of the ECSS standard System Concept Report [ECSS-E-ST-10C, Annex A], and is a constituent of DJF_1.0 (Mission), under the responsibility of the ESA Project Office.

This document, along with the CReMA, is intended as the primary design justification for the overall ATHENA mission architecture and is used [RD 1] in order to derive and justify the allocation of requirements to the Technical Specifications of tier-1 of the Product Tree [RD 35].

Please also refer to DDF_1.0 (Mission), which describes the flow-down from the MRD/ConOps to tier-1, and particularly the technical budgets which are held at mission-level in the MBD [RD 3].

More specifically, this document is composed of two parts:

A. A declaration of the mission scope and capture of the primary constraints and drivers imposed upon the mission including most importantly: Programmatic boundary conditions, user expectations, and any framework or international agreements. This part is used to justify requirements in the MRD in addition to those derived from the SciRD.

B. A top-level description of the envisaged ATHENA mission architecture and operations. This part is used to support the allocation of requirements from the MRD to tier-1 URDs.

Regarding point 2, a primary goal of this document is to provide a referenced-review of the results of the two previous study rounds (IXO/ATHENA_L1), and preliminary work done in Phase 0 of the ATHENA Assessment Phase, in order to define and justify the mission architecture design.

It is important that this document is carefully *read and contributed* to by all stakeholders of the ATHENA mission, particularly the SST who represent the final users, to ensure a common understanding of the mission scope and reference architecture, and to help direct the technical effort.

# 3 MISSION CONSTRAINTS & BOUNDARIES (PART A)

## 3.1 Mission Scope

ATHENA has been selected for the L2-slot with the ESA Cosmic Vision programme to fulfil the selected L2 science theme 'The Hot and Energetic Universe', for a nominal launch in 2028. The scientific objectives of the ATHENA mission are defined in the SciRD (L0/L1/L2) [RD 1], and these are the most important drivers of the mission requirements and subsequent design.

## 3.2 Mission Success Criteria

These are listed in the Risk Document [RD 22].

## 3.3 Mission Architecture

The reference ATHENA functional mission architecture is imposed by the standard ESA approach to observatory missions, and is shown in the following IDEF0 diagram (the mapping of the products to the functions is also shown at the bottom.) The ATHENA mission is composed of 7 tier-1 products.

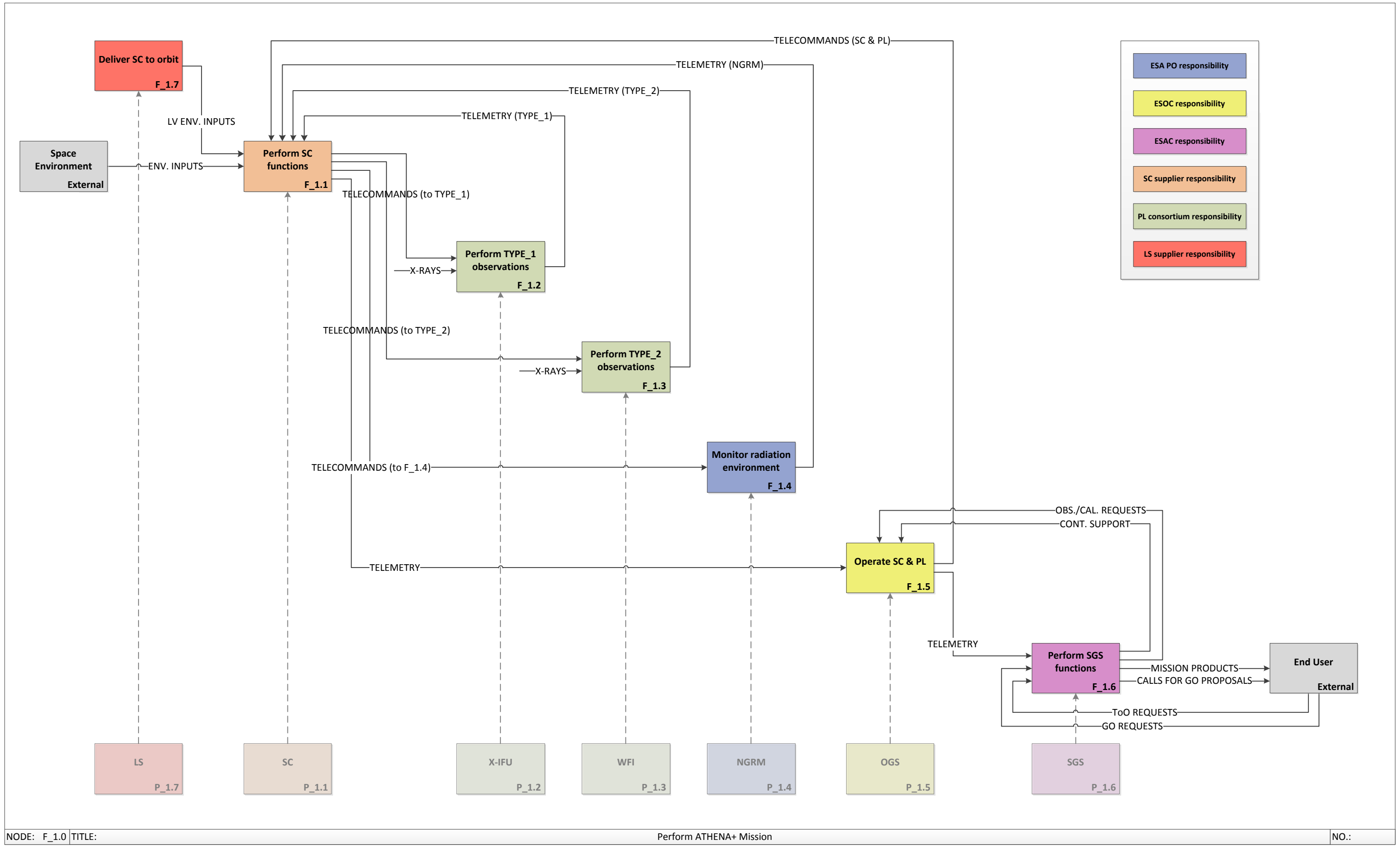


Figure 1: ATHENA reference mission functional architecture in IDEFo format

## 3.4 Mission Boundary Conditions

The ATHENA mission has a variety of other constraints and drivers which must also be reflected in the mission (L3) requirements. The following primary constraints and drivers have been identified:

- Payload (X-IFU and WFI)
- L2 programmatic constraints
  - Schedule
    - Launch date
    - Technology readiness
    - Payload model delivery to Prime
  - ESA Cost at Completion
  - Launcher choice (can be combined with above)
- Geo-return constraints
- ESA approved standards
  - ECSS
  - Space debris
  - Margin philosophy.

Each of these is dealt with in turn in the following sections, and have been reflected in the MRD, and SoW of the industrial assessment studies, where appropriate.

### *3.4.1 Payload*

The reference PL (X-IFU and WFI) is described in the L2 proposal [RD 4]. The reference PL design (which is a response to the L2 requirements in the SciRD) is initially input into the Assessment Phase using the PDD [RD 9], to be superseded by the EID documentation at the time of the AO.

In addition to the reference PL, ATHENA is required to accommodate the Next Generation Radiation Monitor (NGRM) – this is represented for the assessment phase using a specification produced by SRE-F [RD 16], based on the information contained in the ICD for this device [RD 20]. The ICD is treated as a single-sided ICD, made applicable to the SC.

### *3.4.2 L2 Programmatic Constraints*

*Note: Please refer to [RD 10] for a description of the Cosmic Vision programme.*

The Cosmic Vision 2015-2025 Call for L2 Mission Proposals [RD 8] was issued by ESA in January 2014, aimed at defining the large class mission (L mission) to respond to the science theme 'Hot and Energetic Universe'. The resulting programmatic parameters which were contained in the call and which bound the ATHENA mission are presented below.

#### 3.4.2.1 Schedule

ATHENA is required to launch in the year 2028. A baseline schedule has been produced by the ESA Study Team [RD 23], and this is to be used subsequently in the control of the assessment study activities of the Prime and Payload teams in their generation of reference schedules up to PRR (including applicable PL model delivery dates).

*Note: Schedule delays can of course arise in any part of the project, with the result that any part of the system must be compatible with storage. Here we specify ground storage of two years.*

#### 3.4.2.2 CaC

The L2 Call [RD 8] declares that the L2 mission CaC (to be covered by the ESA Science Programme) does not exceed 1B€ at 2013 economic conditions.

#### 3.4.2.3 Technology Readiness

The programmatic requirement is to reach TRL ≥ 5 before the final mission adoption (for all mission elements, platform and payload) (see [RD 8]) – in the baseline schedule this will occur in mid-2019.

*Note: the TRL-scale used by ESA has changed to the ISO standard.*

#### 3.4.2.4 International Cooperation

L-class missions are European-led, but are open to international participation in the form of contributions from international partners. In principle any mission element (i.e. payload, spacecraft, launch, operations, etc.) is open to “international participation”, i.e. to provision of such element from partner agencies from non-ESA member states. However baseline mission contributions from international partners are required to:

- Have a potential replacement that is based on European technology
- Have a combined financial envelope limited to 20% of the total mission cost.

#### 3.4.2.5 Launcher

The launch vehicles compatible with the financial envelope of an L-class mission and available in the timeframe of the L2 Call for Missions are defined in [RD 8] as being the European launch vehicle stable (Vega, Soyuz, Ariane 5). Previous studies indicate that A5 ECA (or the more performant A5 ME) will be required.

The nominated LV is the A64, but A5 ECA performance and I/F information is used until A64 information becomes available.

### *3.4.3 Geo-Return Constraints*

#### 3.4.3.1 Use of European Equipment

Overall geo-return requires that European equipment suppliers are used with a preference. If no alternative can be found, this requirement can be waived.

#### 3.4.3.2 Geo-Return

ESA suffers from a persistent imbalance in geo-return, which is a key clause in article VII (Industrial Policy) of the European Space Agency convention, and the adherence to which is extremely important in order to maintain the member-state funding structure of the agency.

Currently GEODIS constraints are imposed upon the costing for the Phase A studies.

### *3.4.4 ESA Approved Standards*

#### 3.4.4.1 ECSS

The ESA approved standards list [RD 12] defines the standards in the Management, Product Assurance, and Engineering disciplines to be used in implementing all ESA project space activities in accordance with [RD 12]. This list of standards is made applicable to the ATHENA mission.

*Note: tailoring is TBD.*

The most important ECSS-standards at mission-level are discussed in the following sections.

##### *3.4.4.1.1 Environment*

The ATHENA Environmental Specification [RD 15] has been generated and applied to the SC.

##### *3.4.4.1.2 Space Debris*

The European Code of Conduct for Space Debris Mitigation [RD 13] has been developed on a cooperative basis amongst interested space agencies in Europe to identify those practices which serve to minimizes the impact of space operations on the orbital environment. ATHENA must adhere to the standard, which implies that an EoL disposal of the SC must occur to prevent the SC returning to the Earth via WSB and re-entering the atmosphere in an uncontrolled manner.

##### *3.4.4.1.3 Operability*

The SC will have to I/F with the ESTRACK network of GS. This is governed by the operability standard ECSS [RD 25]. The operability and autonomy requirements on the SC imposed by the mission architecture are discussed in §4.3 of this document.

During the initial Phase 0/A, the I/F with the ESTRACK network is governed by the ESTRACK Facilities Manual [RD 17]. This is then superseded during Phase B1 by the OIRD, which specifies the I/F and operability requirement from the OGS to the SC, and which is an instantiation of the Operability ECSS.

#### 3.4.4.2 Margin Philosophy

SRE-F maintains an assessment phase margin philosophy which is required to be followed for Phase 0/A studies [RD 14], and has therefore been made applicable to the MRD.

## 3.5 Expected Form of the Multi-Lateral Agreement

The anticipated form of the MLA is reflected in the colour-coding scheme used in the ATHENA Function, Product and Specification trees, and the WBS (also see Figure 1).

## 3.6 User Expectations on Data Products

TBW.

# 4 MISSION CONCEPT (PART B)

The baseline mission concept is presented here, making use of previous study rounds where appropriate to fix the following:

- Transfer & Operational Orbit
- Ground segment & band (coverage scenario etc.)

## 4.1 Orbit

### *4.1.1 Previous Study Results*

The IXO Study reference orbit was a large-amplitude (2x10^6km) Halo at L2 – this was taken as a given by the IXO CDF study [RD 26], and reported in the IXO CReMA [RD 27]. No evidence of any T/O regarding the orbit selection has been found in the IXO AP documentation (TBC.)

During the ATHENA_L1 Internal Study [RD 28] a mission profile trade-off was conducted between (i) a low-inclination, low-altitude orbit (<3° i, 600 km altitude) reached with Soyuz-Fregat from Kourou, and (ii) a large halo orbit around L2, reached with A5 ECA from Kourou (LV capacity ~6 tonnes in both cases). L2 was selected for a number of reasons (see table below.)

Table 1 – Orbit trade-off performed during the ATHENA_L1 Internal Study (taken from [RD 28])

| Scenario | Equatorial LEO (Soyuz-Fregat) | Large halo at SE-L2 (Ariane 5) Direct transfer |
|---|---|---|
| Pro's | Lower LV cost<br>Adequate launch mass (> 5.5 ton)<br>Low radiation background<br>Frequent contact with S/C | Stable thermal environment.<br>Eclipse free over > 5 yr<br>Max F ~11.5m (no EOB).<br>Adequate launch mass (6.5 ton)<br>Environment & ops well known to ESA |
| Con's | Max F ~6 m, forcing to EOB<br>Very complex TCS<br>Continuous eclipses<br>G/S update required | Higher LV cost<br>Less favourable radiation background<br>Less frequent contact with S/C |

Some further points can be added to this T/O:

- The equatorial LEO orbit is similar to the baseline of the recently studied x-ray mission LOFT (i<2.5°, 550km). The orbital period at this altitude is ~100min, and ~35min per orbit eclipse of the target will occur for all except high-declination targets above ~70° galactic declination – see the following figure. This one source of interruption immediately constrains the observation availability to below 65%; this can be compared with the 75% (TBC) availability requirement for ATHENA on the basis of the decomposition of net observing times in [RD 3] and would imply several additional years of operational lifetime to achieve the net observing time requirements specified in the SciRD [RD 1]. Furthermore the thermal environment in equatorial LEO is widely and, because of varying cloud-coverage, to a large degree unpredictably varying. Problems with the thermal I/F for the CC could be envisaged if this orbit is selected.

- L2 is a well-known environment for SC design, but it is cautionary to note that the radiation environment worsens with increasing orbit amplitude around L2 as the orbit interacts with Earth's magnetotail. Currently there is no indication that the radiation environment in the reference large-amplitude Halo orbit (with maximum SSE angle of 32° (TBC) is problematic for the ATHENA PL. If this should change then a reduction in Halo-amplitude as discussed in the CReMA [RD 5] could be considered, but note that this would require a significant increase in dV as a free-insertion would no longer be possible (e.g. an extra ~104ms-1 to reduce the SSE angle to 20° after a 120 day transfer, more than doubling the ΔV budget). The required EoL disposal ΔV is also likely to increase from a small-amplitude orbit.

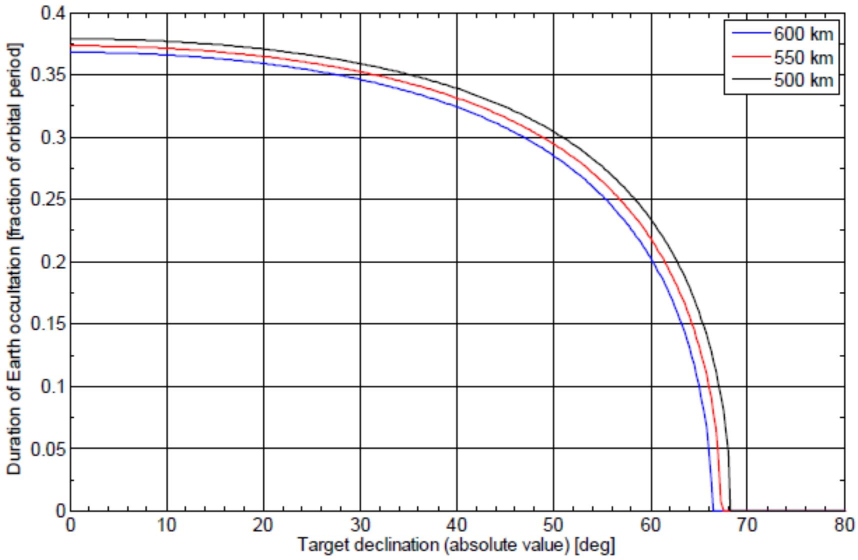


Figure 2 – Duration of target occultation by the Earth as a fraction of orbital period for low altitude equatorial orbits

### *4.1.2 Reference Orbit*

The required orbit for the ATHENA mission is defined in the L2 proposal as being a large-amplitude (Halo) orbit at Libration Point 2. The reference mission scenario is described in detail in the CReMA [RD 5], consisting of a launch using A5[1] ECA, and then a WSB free-transfer with to the Halo orbit.

## 4.2 TT&C band, Ground Segment & Coverage

### *4.2.1 GS-Selection*

The ground-station is required to be one of the 35m deep space antennas: Accordingly Cebreros, New Norcia or Malargue can be considered. Since ESOC will be responsible for the operation of the satellite the stations in New Norcia and Malargue are preferred, since the SC will be at L2 libration point and thus the antenna will have SC visibility while ESOC

[1] Note that the uncertainty surrounding the availability of A5 ECA/ME in 2028 is one of top risks for ATHENA.

is on the day side of the Earth; this allows nominal operations to take place during daytime working hours.

### *4.2.2 Bandwidth Trade-Offs*

For frequency coordination, ATHENA is classified as a Near Earth (Cat. A), Space Research (SR) mission [RD 29]. This restricts the frequency bands it is entitled to make use of for the download of its scientific data. In the following sections, a short overview is given of frequency bands available for Space-to-Earth links together with a short description of their allocation and possible constraints. X-band and K-band are the only viable options for the ATHENA mission.

#### 4.2.2.1 X-band (8450 – 8500 MHz)

This band is currently used/planned by ESA L1/L2 missions such as GAIA, LISA Pathfinder, and Herschel/Planck. The band is only 50MHz wide, with the bandwidth available for a single mission limited to a maximum of 10MHz. Assuming current ESA supported modulation schemes (e.g. GMSK) and allowing some margin due to spectral regrowth from non-linear amplification, a symbol rate of 10Msps is typically considered to be the maximum possible in this band. The daily data volume then depends on the coding scheme selected and the daily communication time.

ESA's GAIA mission provides a good reference for the maximum daily data return in the X-band. In particular, using RS coding concatenated with a punctured convolutional code with rate ¾, a total data rate of 6.54Mbps can be supported. In order to increase the data rate, it is possible to reduce the level of coding, provided the received power is enough in order to get the desired performance: with RS only, up to 8.74Mbps data rate is possible. Higher order modulation schemes (e.g. 8- or 16-APSK, not currently supported by the standard) and, dual polarisation are in principle technically possible. This could theoretically lead to data rates in the order of 25Mbps within the 10MHz bandwidth but there are problems:

- Low signal to noise ratio (for X-band because of high order modulation and the required low symbol/bit ratio for the coding)
- Weather and elevation dependant (because of dual polarisation)
- Requires new development and changes to current standard.

#### 4.2.2.2 K-band (25.5 – 27 GHz)

The 25.5 – 27GHz band (sometimes referred to as the '26GHz band') frequency allocation was agreed at the World Radio Conference in 2003. This 1.5GHz wide band has been allocated to Space Research and Earth Exploration Satellites Services and targets those missions which cannot meet their very high data rate requirements in the tight X-band (e.g. L2 missions requiring more than 10Msps or Earth Exploration missions requiring > 500Mbps).

At present, no official bandwidth restrictions exist in this frequency band nor are there recommended modulation and coding schemes. However, efficient use of the band is encouraged.

At the time of ATHENA, because of EUCLID requirements, both Cebreros and Malargue will by 26Ghz (K-band) capable. The interest in K-band for ATHENA lays in the possibility to download the payload over relatively short period of time, reducing the use of the G/S. For example, with a data rate of 55Mbps, it would be possible to download the peak daily data payload (worst case) with passes of around 30 minutes (compared to the 4 hours needed in X-band).

### 4.2.3 Previous Studies on TT&C architecture

IXO CDF: At this time the PL TM-generation rate was evaluated as, on average, 43Gbit/day (local peaks of 130Gbit/day could occur). This TM-load was comfortably accommodated by the selected X-band system with 35m GS (baseline New Norcia, backup Cebreros), using GMSK and RS-coding (255,223) code.

Consequently X-band was selected for the download of the science payload of IXO during Phase 0. During Phase A of the IXO AP the MRD [RD 30] did not specify the band to be used, but both Prime contractors also selected X-band [RD 31], [RD 32].

The costs relative to the use of K band, e.g. new development for the space and ground segment, are not considered justified: the mission targets can be achieved in X band, using consolidated technology and way of operations.

The ATHENA_L1 Assessment Phase: At this time the PL TM-generation rate was evaluated as ~90Gbit/day maximum. The resulting chosen baseline architecture was essentially identical to that chosen for IXO: X-band system to a 35m GS (e.g. New Norcia, Cebreros), providing a TM-rate of at least 8Msps, leading to a daily average TM-capability of ~86Gbit/day. This conclusion was supported by industry.

### 4.2.4 Reference TT&C Architecture

*Considering the reference operational analysis described in the MBD [RD 3], which implies a long-term average TM-rate of ~100Gbits/day, it is currently foreseen to use the SR X-band allocation with RS coding to achieve ~8.74Mbps, allowing the mission product to be downloaded with daily 4h ground passes to New Norcia, with 3.5h of down-link duration.*

## 4.3 Autonomy

*Note: Space segment (SC & PL) autonomy is governed by the Operability ECSS standard [RD 25]. The most important autonomy requirements of the SC and PL are derived here on the basis of the operational scenarios described in this document.*

### 4.3.1 SC Autonomy

The ATHENA SC shall have a 'standard' level of autonomy in order to limit the operational effort on the ground; in particular the level of coverage (e.g. no double coverage is required), and also to reduce the criticality of non-nominal scenarios. Discussion with ESOC has led to the following requirements for autonomy on the ATHENA SC:

- During LEOP: autonomous nominal operation w/o ground contact for 12 hours
- In all mission phases after LEOP:
  - Autonomous nominal operations w/o ground contact for at least 3 days
  - Survival (Safe Mode) w/o ground contact for at least 7 days.

These 'general autonomy' requirements conform to section 5.7.2 of the ECSS standard, with the associated <constants> filled in:

Table 2: ATHENA general SC autonomy requirements

| Constant | Value |
|---|---|
| <ANOM_RESP_TIME> | 7 days |
| <AUT_DUR_EXEC> | 1 day (12 hours LEOP) |
| <AUT_DUR_DATA> | 1 day |
| <AUT_DUR_FAIL> | 7 days |

Generally speaking, the SC is required to have:

- Autonomy for execution of nominal mission operations: autonomy-level E2 (execution of re-planned, ground-defined, mission operations on-board), Table 5-1: ECSS-E-ST-70-11C.
- Autonomy for mission data management: autonomy-level D2 (all mission data can be stored on-board), Table 5-2: ECSS-E-ST-70-11C.
- On-board fault management: autonomy-level F1 (autonomy to safeguard the space segment or it's sub-functions), Table 5-3: ECSS-E-ST-70-11C.

### 4.3.2 PL Autonomy

Given the high-level of activity in the OGS in support of the LEOP and TP, it is necessary that the PL (each of the two instruments and the NGRM) do not impose any requirement on the ground segment (OGS & SGS) to perform extensive PL operations for an interval <PAYLOAD_INT> after separation from the launcher. Simple PL operations such as switch-on or heater activation can be permitted.

## 4.4 Mission Timeline

*Note: the reference timeline is used as the justification for several requirements in the MRD.*

ATHENA will follow a standard mission phase definition used by ESA:

- Pre-Launch Phase [PLP]
- Launch & Early Operation Phase [LEOP]
- Transfer Phase [TP]
- Commissioning Phase [CP]
  - Performance Verification Phase [PVP]
  - Science Demonstration Phase [SDP]
- Nominal Operations Phase [NOP]
- Extended Operations Phase [EOP]
- Decommissioning Phase [DP]
- Post-Operations Phase [POP] – SGS only
- Active-Archival Phase [AAP] – SGS only.

See Table 3 for an overview of the mission timeline. For each mission phase, this section will provide:

- Phase Overview & Timeline of principal events
- Discussion of each principal event
- Ground coverage.

Table 3: ATHENA mission timeline

| Event | Time relative to T0 | Manoeuvre magnitude | Manoeuvre direction constraints | Manoeuvre accuracy constraints | References | Comment |
|---|---|---|---|---|---|---|
| PLP | (TBD)d | | | | | |
| | | | | | | |
| LEOP | T0 | | | | | |
| Launch | 0 | - | - | - | | |
| SC separation from LV | 30min (TBC.) | - | TBD (The ATHENA telescope will have a light-tight cover to protect against contamination TBC, so no LOSSAA constraints should exist.) | State-vector and dispersions to be provided to the SC by the LV. | CReMA:<br>§2.4, table 2.5, p.10 for separation state.<br>§4.2.2, table 4.1/4.2, p.27 for required LV dispersions and correlation factors.<br><br>A5 User Manual:<br>§2.6. | A5 ECA launch. The CReMA assumes that the LV provides the same dispersions as for the Herschel Planck launch scenario.<br><br>GTO mission durations typically 25-35 minutes; actual duration specific to the mission.<br><br>The current baseline is 3-axis stabilised separation TBC (no need identified for spin-stabilised, and relaxes CoM requirements on SC.) |
| State Vector (SV) tracking | 30min - 2d | - | - | - | CReMA:<br>§4.1, p.25. | The SC must perform TCM#1 within T0+2 days in order to constrain the magnitude of the V_perigee error part of TCM#1. |
| Initial Commissioning | 30min - 2d | - | - | - | CReMA:<br>§4.1, p.25. | Focused on making SC ready to perform TCM#1. |

| Event | Time relative to T0 | Manoeuvre magnitude | Manoeuvre direction constraints | Manoeuvre accuracy constraints | References | Comment |
|---|---|---|---|---|---|---|
| Perigee velocity correction (part of TCM#1) | up to 2d (nominal 24h after T0) | 12.7ms-1 to 99% confidence. | (Anti) parallel to the SC velocity vector; the velocity vector lies in two cones with 35◦ half cone angle around the Sun- Earth and Earth-Sun vectors (in the synodic rotating frame). | Magnitude error: 3% or 6mm.s-1 maximum for manoeuvres less than 20cm.s-1.<br>Direction error: 0.75◦.<br>Both to 99.7% confidence.<br><br>Additional constraint: manoeuvre to be performed in less than 2 hours. | CReMA:<br>§4.3, p.29 for manoeuvre duration reference (must be less than 2 hours).<br>§3.3, fig. 3.4, p.15 & §4.2, p.26 for manoeuvre timeliness. | The required V_perigee to reach L2 is affected by the launch date - the restricted number of launcher programmes means a deterministic error between programmed and required V_perigee will usually be present(note that perigee velocity correction has been reduced IXO>ATHENA.)<br><br>Derived by considering a modulus 1.5ms-1 limit on the difference between programmed and required V_perigee, which in turn allows 3-weeks per month launch window availability. Performing the manoeuvre within 2 days of launch restricts amplification factor to ~8.<br><br>Duration constraint to allow assumption of an impulse manoeuvre to be valid (~0 gravity losses.) |
| LV dispersion correction (part of TCM#1) | up to 2d (nominal 24h after T0) | 36.3ms-1 to 99% confidence. | (Anti) parallel to the SC velocity vector; the velocity vector lies in two cones with 35◦ half cone angle around the Sun- Earth and Earth-Sun vectors (in the synodic rotating frame). | Magnitude error: 3% or 6mm.s-1 maximum for manoeuvres less than 20cm.s-1.<br>Direction error: 0.75◦.<br>Both to 99.7% confidence. | CReMA:<br>§4.2.2, Table 4.4, p.18., for magnitude.<br><br>§4, figure 4.2, p.30 for manoeuvre direction constraints. | 99% confidence dV magnitude, as long as the launch dispersion conditions are met (see 'Launch' entry above.) |
| TP | 2d | | | | | |
| State Vector tracking | 2d - 5d | - | - | - | CReMA:<br>§4.1, p.24. | Preparation for TCM#2. |

| Event | Time relative to T0 | Manoeuvre magnitude | Manoeuvre direction constraints | Manoeuvre accuracy constraints | References | Comment |
|---|---|---|---|---|---|---|
| Further commissioning | 2d - 5d | - | - | - | CReMA:<br>§4.1, p.24. | Further commissioning not defined. |
| TCM#2 | 5d | 2.47ms-1 | 15◦ half-angle cone around the unstable direction of linear theory, +28.5◦ [+ve] or +208.5◦ [-ve] from the Sun-line. | Magnitude error:<br>3% or 6mm.s-1 maximum for manoeuvres less than 20cm.s-1.<br>Direction error:<br>0.75◦.<br>Both to 99.7% confidence. | CReMA:<br>§2.2, Figure 2.1, p.5 for direction.<br><br>§4.2.2, Table 4.4, p.18 for magnitude. | 99% confidence magnitude (note not related to launcher dispersion.) |
| TCM#3 | 20d | 0.24ms-1 | 15◦ half-angle cone around the unstable direction of linear theory, +28.5◦ [+ve] or +208.5◦ [-ve] from the Sun-line. | Magnitude error:<br>3% or 6mm.s-1 maximum for manoeuvres less than 20cm.s-1.<br>Direction error:<br>0.75◦.<br>Both to 99.7% confidence. | CReMA:<br>§2.2, Figure 2.1, p.5 for direction.<br><br>§4.2.2, Table 4.4, p.18 for magnitude. | 99% confidence magnitude. Note not related to launcher dispersion.<br><br>Marks the end of TP. |
| CP | 20d | | | | | |
| Commissioning activities | 20d-90d | - | - | - | | |
| Mirror Assembly cover removal. | 30d | - | - | - | - | This is prescriptive -if we can confidently assert such an object is needed then we can include it. Need to establish that it won't collide with the SC once released. |

| Event | Time relative to T0 | Manoeuvre magnitude | Manoeuvre direction constraints | Manoeuvre accuracy constraints | References | Comment |
|---|---|---|---|---|---|---|
| Orbit-maintenance manoeuvres (inc. provision for Safe Mode events.) | every 30d after TCM#3 | 1.302 ms-1y-1 | 15◦ half-angle cone around the unstable direction of linear theory, +28.5◦ [+ve] or +208.5◦ [-ve] from the Sun-line. | Magnitude error: 3% or 6mm.s-1 maximum for manoeuvres less than 20cm.s-1. Direction error: 0.75◦. Both to 99.7% confidence. | CReMA: §5.3.5, p.39 for guidance on station-keeping budget calculation. MBD for derivation of station-keeping budget. | TBD can be calculated based on the method described in the CReMA (spreadsheet provided.) |
| NOP | 90d | | | | | Duration of NoP is TBD. |
| Observations | Continuous | - | - | - | Observation Plan document. | - |
| Orbit-maintenance manoeuvres (inc. provision for Safe Mode events.) | every 30d after TCM#3 | 1.302 ms-1y-1 | 15◦ half-angle cone around the unstable direction of linear theory, +28.5◦ [+ve] or +208.5◦ [-ve] from the Sun-line. | Magnitude error: 3% or 6mm.s-1 maximum for manoeuvres less than 20cm.s-1. Direction error: 0.75◦. Both to 99.7% confidence. | CReMA: §5.3.5, p.39 for guidance on station-keeping budget calculation. MBD for derivation of station-keeping budget. | TBD can be calculated based on the method described in the CReMA (spreadsheet provided.) |
| EOP | (TBD)d | | | | | Duration of EoP is TBD. |
| Same as NOP | | | | | | |
| DP | (TBD)d | | | | | |

| Event | Time relative to T0 | Manoeuvre magnitude | Manoeuvre direction constraints | Manoeuvre accuracy constraints | References | Comment |
|---|---|---|---|---|---|---|
| DISP#1 | TBD | 10ms-1 | TBD | Magnitude error: 3% or 6mm.s-1 maximum for manoeuvres less than 20cm.s-1. Direction error: 0.75◦. Both to 99.7% confidence. | CReMA: §6, p.41. | Heliocentric disposal. |
| POP | (TBD)d | | | | | |
| | | | | | | |
| AAP | (TBD)d | | | | | |
| | | | | | | |

### 4.4.1 PLP

During the SC development, some key characteristics of the SC will facilitate the development. The SC should be configured in a modular way such that:

- Constituent elements can be individually integrated and tested. Simple mounting/dismounting procedures should be used such that items such as the payloads can be installed/removed late in the integration sequence.
- Transportation of the complete SC as well as its modular elements can be achieved by standard commercial means (the ATHENA SC will be very large).

### 4.4.2 *Launch & Early Operations Phase (LEOP)*

#### 4.4.2.1 Overview & Timeline

ATHENA will undergo the following sequence of main events during LEOP:

- Launch on A5 ECA or ME from Kourou
- Separation from LV after tracking of SV; autonomous detection of separation from the LV and autonomous activation of TT&C Tx/Rx
- Rate-damping and acquisition of a safe attitude with solar arrays deployed and generating power
- Initial commissioning
- LV dispersion (and programme error) correction manoeuvre (TCM#1).

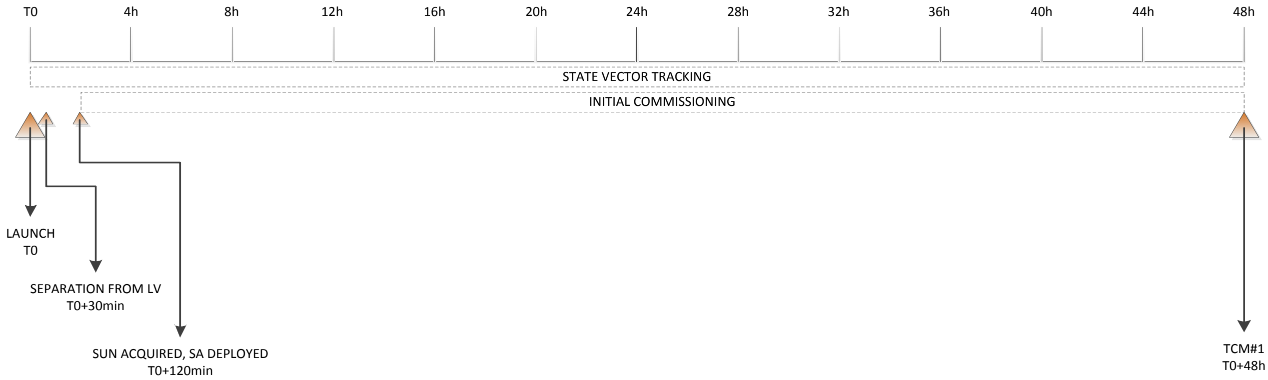


Figure 3: LEOP timeline showing principal events (relative to T0)

#### 4.4.2.2 Launch on A5 ECA/ME (or Atlas V)

A representative launch scenario is shown in the following figure (from Arianespace). The precise timeline is TBD.

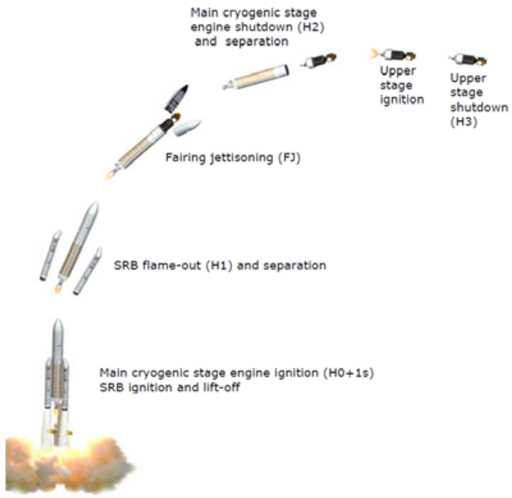


Figure 4: A5 launch typical series of events

Note that, in order for the ΔV budget for launcher-dispersion correction (see below) to be valid, the LV needs to provide the transfer orbit and dispersions specified in the CReMA – the validity of the ΔV budget rests upon A5 providing these dispersions. These are important requirements which are imposed upon the LS in the MRD.

##### *4.4.2.2.1 Launch Windows*

See the CReMA.

#### 4.4.2.3 Rate-damping & Sun-acquisition

TBW.

#### 4.4.2.4 TCM#1

TCM#1 is the first SC manoeuvre, required to:

i. remove the error due to the LV-dispersion

ii. correct the difference between the required perigee velocity ($V_{p\_req}$) to enter the stable manifold, and the $V_{p\_LV}$ supplied by the LV programme. This difference is necessary to limit re-programming of the LV, and determines the number of launch opportunities per year; a maximum difference $|V_{p\_LV} - V_{p\_req}| = 1.5ms^{-1}$ provides a launch window of ~3 weeks per month (see CReMA fig. 3.5.)

The component of the magnitude of TCM#1 required for (i) is $36.3ms^{-1}$ (to 99% confidence) *as long* as the LV dispersion conditions are met (see above.)

The timeliness of TCM#1 is critically important because the required ΔV magnitude to correct (ii) grows exponentially with time. The reference scenario envisages that this manoeuvre shall occur no later than T0+2d, in order to restrict the amplification factor of the velocity error to ~8, resulting in 12.7ms-1 allocated in the ΔV for this component of the manoeuvre.

The direction of TCM#1 is (anti)-parallel to the velocity vector, which is constrained to be within 35° of the Sun-Earth vector. Accordingly there are strong requirements imposed on the SC (to be designed and sufficiently commissioned to perform the manoeuvre) and the OGS (to track and command the manoeuvre) within 2 days of launch.

TCM#1 must also be performed within 2h in order for impulse-assumption used in the ΔV budget to remain valid.

*Note: A typical operational requirement from ESOC is that the SC shall provide on-board and in telemetry the achieved velocity increment for every delta-V manoeuvre with accuracy equal or better than 1.5% of the delta-V magnitude to a confidence of 99.7%.*

*Note: ESOC requests that the SC shall perform all manoeuvres with a delta-V vector with less than: 3% (or 6 mm/s for manoeuvres smaller than 20 cm/s) delta-V magnitude error; 0.75° directional error, to a confidence of 99.7%. These accuracies provide margin against those declared in the CReMA.*

#### 4.4.2.5 Ground Support & Coverage

During LEOP a 3-station quasi-continuous coverage (tracking and uplink) will be provided using the baseline New Norcia 35m station, with Kourou and TBD as additional stations. TT&C ranging is a required functionality for the SC.

### 4.4.3 Transfer Phase (TP)

#### 4.4.3.1 Overview & Timeline

ATHENA will undergo the following sequence of main events during the TP:

- SC tracking & further commissioning
- TCM#2
- TCM#3

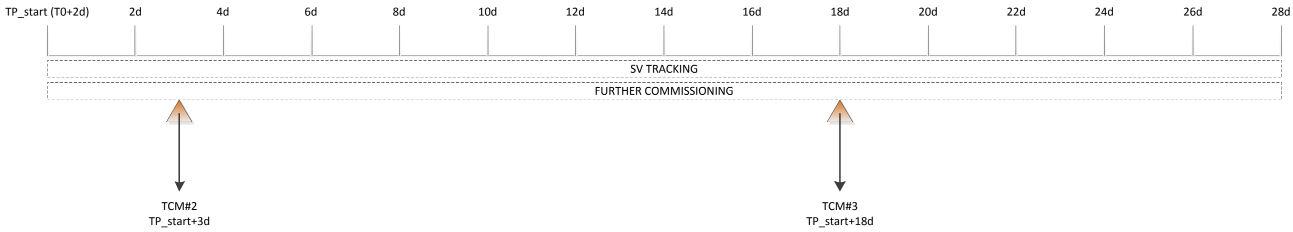


Figure 5: TP timeline showing principal events (relative to TP_start which is To+2d)

#### 4.4.3.2 SC tracking & further commissioning

TBW.

#### 4.4.3.3 TCM#2

TCM#2 is required to correct for the errors of TCM#1 and to further remove the unstable component of the trajectory. The maximum required magnitude of this manoeuvre is $2.47ms^{-1}$ (to 99% confidence). The manoeuvre direction is in the unstable (escape) direction (+ve or –ve) of the linear restricted circular three-body problem (+28.5◦ or +208.5◦ from the Sun-direction, parallel to the ecliptic plane.)

#### 4.4.3.4 TCM#3

TCM#2 is required to place the SC precisely on the stable manifold of a large amplitude Halo-orbit around L2. The maximum required magnitude of this manoeuvre is $0.24ms^{-1}$ (to 99% confidence). The manoeuvre direction is the same as for TCM#2.

#### 4.4.3.5 Ground Support & Coverage

In addition to daily New Norcia passes during transfer (TBD duration) support from the Malargüe station will be added as required for tracking, manoeuvre monitoring, and deployment.

### 4.4.4 Commissioning Phase (CP)

#### 4.4.4.1 Overview & Timeline

ATHENA will undergo the following sequence of main events during the CP:

- Further commissioning
- OCM every ~30d

The CP will be considered complete once the SC and PL are fully commissioned.

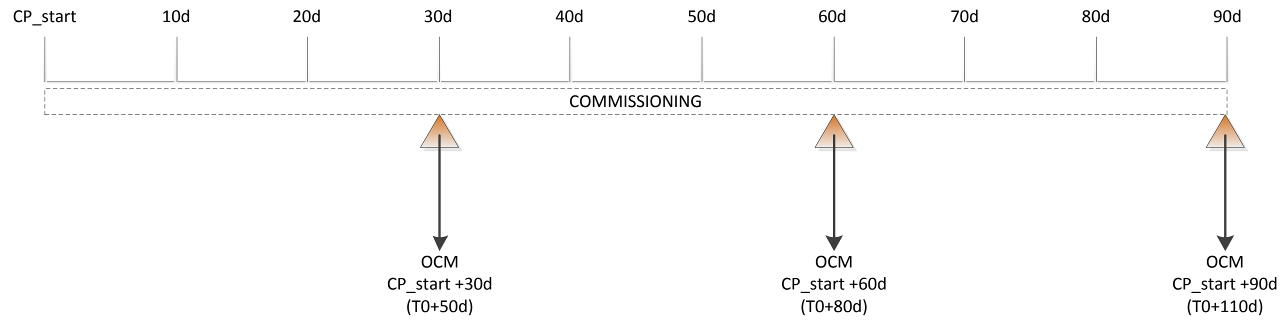


Figure 6: CP timeline showing principal events (relative to CP_start which is To+20d)

#### 4.4.4.2 SC tracking & further commissioning

The detailed commissioning timeline is TBD, but in order to constrain overall mission operations costs, it is required to be completed within T0+110d.

#### 4.4.4.3 Orbit Control Manoeuvres

All orbits around L2 are unstable. Consequently OCM manoeuvres are required every ~30d throughout the mission from the CP onwards to maintain the orbit around L2. These manoeuvres are compensating for stochastic processes (SC noise etc.) and their magnitudes are heavily dependent upon the uncharacterised noise of the SC. The rules governing the magnitude are provided in the MBD [RD 3].

The manoeuvre direction is in the unstable (escape) direction (+ve or –ve) of the linear restricted circular three-body problem (+28.5° or +208.5° from the Sun-direction, parallel to the ecliptic plane.)

#### 4.4.4.4 Ground Support & Coverage

Daily New Norcia passes (up to 10h/day) will be scheduled during commissioning.

### 4.4.5 *Nominal & Extended Operations Phase (NoP & EoP)*

*Note: See the SOAD [RD 7] the ATHENA observation plan [RD 19] and the SciRD [RD 1] for more information concerning science operations and target types.*

#### 4.4.5.1 Overview & Timeline

ATHENA will undergo the following sequence of main events during NoP/EoP:

- Scheduled Observations
  - Core Science
  - Guest Observer
- ToO Observations
- OCM every ~30d.

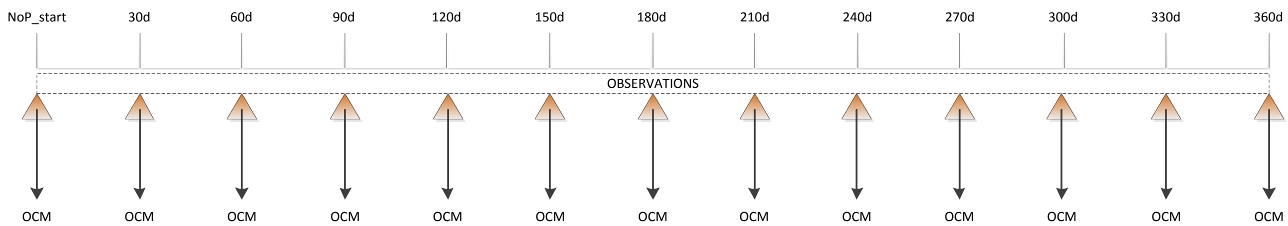


Figure 7: NoP/EoP 1-year timeline showing principal events (relative to CP_start which is To+20d)

##### *4.4.5.1.1 Field of Regard*

See the Acronyms and Definitions document [RD 37] for a definition of the FoR. Close to the ecliptic the FoR is mapped onto the x-ray sky as two bands, depending on the angles $\alpha_1$ and $\alpha_2$, which will move along the ecliptic as the FoR rotates with the orbit of the Earth around the Sun. At the celestial poles the coverage will be better, and constant for a FoR where $\alpha_1$ and $\alpha_2$ are greater than the obliquity of the Earth (~23.4°). It is readily apparent that under these conditions the FoR will cover the entire sky in less than 6 months.

##### *4.4.5.1.2 Net Observing Times*

See the MBD [RD 3] for the derivation of the NoP and EoP durations, from the Mock Observing Plan [RD 19].

##### *4.4.5.1.3 Reference Observation Sequence*

See the Mock Observing Plan [RD 19].

#### 4.4.5.2 Scheduled Observations

ATHENA will observe a wide-variety of x-ray sources spread across the celestial sky. There will be around 300 such observations per year, with durations ranging from 1ks to 1Ms, with a typical duration of 100ks per pointing.

The observatory will have a set of standard operating modes (including normal pointing, manoeuvre, sun hold, and safe-mode), and a limited number of standard well-defined and calibrated science observing modes. Automated responses to contingency situations such as high levels of solar radiation can place the instruments into a safe configuration, and to later resume operations efficiently as soon as the alert has passed. ATHENA requires only standard ground-station coverage during launch, activation, cruise, and injection to L2. The orbit station-keeping and other L2 orbital characteristics do not in themselves require special coverage either.

#### 4.4.5.3 Observation Modes

In addition to persistent observations in a fixed direction (either sustained observations of a single target with the X-IFU instrument, or of a wide-field with the WFI), it is envisaged that ATHENA shall be able to, when appropriate, perform dithering to disentangle detector effects from true features in the observed objects. The anticipated dithering modes are sub-divided into Raster Scan & Lissajous Modes.

##### *4.4.5.3.1 Raster Scan Mode*

Typical long observations, used to observe weak sources, could be split into different pointings constituting a Raster scan of the target. As a minimum a Raster scan with 9 observations centred on the target under observation and separated by 2 PSFs (10'') 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 = 10'' (2xPSF HEW). T_exp is expected to be ~2.5ks, then T_long ~ N*M*T_exp.

##### *4.4.5.3.2 Lissajous Mode*

In alternative to different pointings, a continuous dithering pattern (such as a Lissajous figure) could be used to cover a typical region of 20''x20'' around the target, and could be used for pointing 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 continuous scan in directions parallel with the instrument axes. The amplitude of scan shall be +/-10'' from the initial inertial pointing direction. The period of one complete cycle in each axis shall be a configurable parameter, but typically 1200 seconds in axis X and SQRT(2)x that period in axis Y. A number of cycles would be repeated to cover the total duration of T_long.

#### 4.4.5.4 ToO Observations

##### *4.4.5.4.1 ToO Characteristics*

*Note: Please refer to the MBD [RD 3], for the derivation of ToO-response speed from ToO distribution and frequency.*

ATHENA will start operating in the late 2020s when the pre-eminent facilities operating at other wavelengths are expected to include LOFAR, SKA, ALMA, JWST, E-ELT, LSST and

CTA. Follow-up or coordinated observations with such facilities can provide complementary data to enhance the understanding of a wide range of astrophysical phenomena. The ATHENA surveys, the ATHENA follow-up observations of high-z GRBs or clusters discovered at high redshifts in SZ surveys are examples where this complementary between facilities will be essential.

Accordingly it is anticipated that the routine observing plan will be interrupted by GRB-ToOsobservationsat a rate of ~2 a month. For these, extremely fast response-times (<4 hours) will be required in order to capture the GRB-afterglow at the required fluence. Non-GRB-ToOs will also occur, but these will not require such quick response-times (<12 hours).

In the case of GRBs observations, the trigger for high-z candidates will likely have to go through automated ground-based observations with robotic telescopes, as is already the case currently.

#### *4.4.5.4.2 Previous Study Rounds*

[IXO CDF]: The ToO concept operated on best-effort basis using any available ESTRACK X-band antenna. EDRS was explored as an alternative, but rejected.

ATHENA_L1 Assessment Study: As IXO.

#### *4.4.5.4.3 Baseline ToO-reaction Architecture*

*Note: Please refer to the ToO-Response T/O document [RD 33] for the justification and full description of the baseline ToO architecture.*

The baseline ToO architecture follows the sequence of events shown in the following figure.

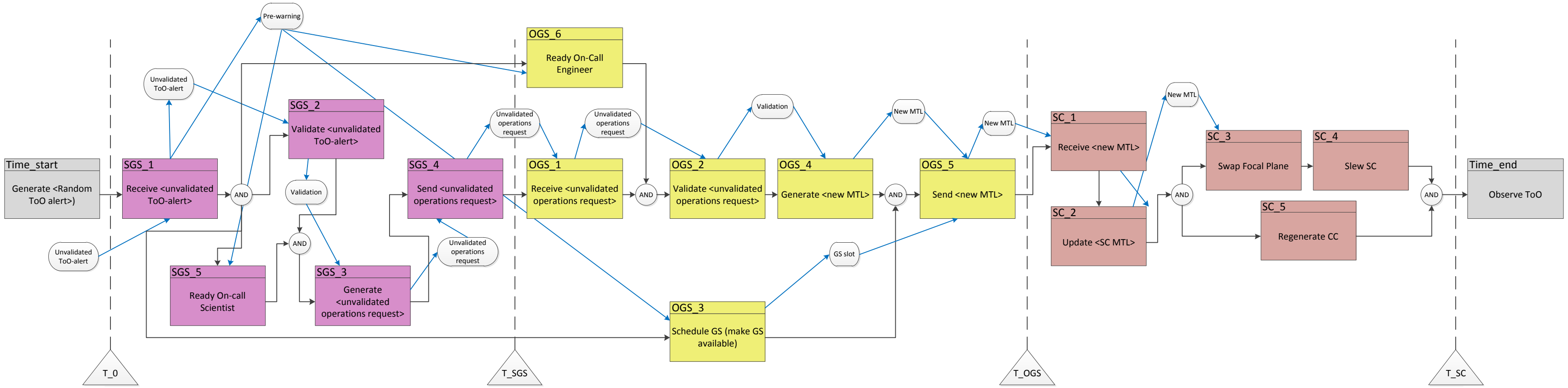


Figure 8: ToO-response FFBD

#### 4.4.5.5 Orbit Control Manoeuvres

*As per §4.4.4.3.*

#### *4.4.5.6* Ground Support & Coverage

For nominal TM/TC, only one ground station is allocated for communications with the SC during the NoP/EoP operations. The station coverage is minimised matching the needs for science data downlink, tracking, and monitoring and control. Daily New Norcia passes (4h/day) will be scheduled during operations phase.

For ToO-uplinks, the architecture as described in §4.4.5.4.3 is used.

### 4.4.6 Decommissioning Phase (DP)

ATHENA will undergo the following sequence of main events during DP:

- Downlink of residual science and housekeeping telemetry: TM DL
- DP_start+10d: DISP#1 manoeuvre
- DP_start +100d: DISP#2 manoeuvre
- DP_start +110d: Passivation
- DP_start +120d: EOM.

The timeline (relative to DP start) is shown in the following figure. The DP is considered to be finished at EOM.

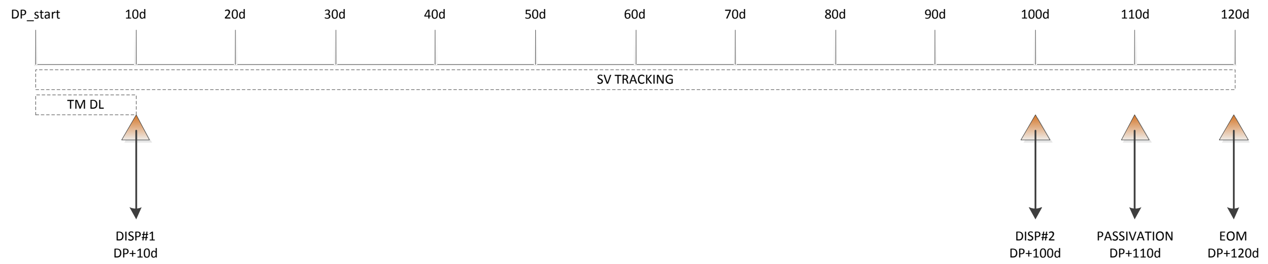


Figure 9: DP timeline (relative to DP_start which is T0+TBDdays.)

#### 4.4.6.1 SV Tracking & Residual Telemetry Downlink

At the end of EoP it is anticipated that some science telemetry will still be present in storage on the SC. Accordingly, in parallel with state-vector tracking in preparation for DISP#1, a dedicated period could be used at the beginning of the DP to down-link the remaining TM to the GS; an increase in the ground coverage profile could be considered to facilitate/shorten this activity.

#### 4.4.6.2 Disposal Manoeuvre

Whilst, according to [RD 13] L2 is not currently a protected region, return of the ATHENA SC to the protected LEO (and associated non-zero risk of re-entry) and GEO regions from L2 (along a WSB, in a reversal of the means which is used to achieve a low-cost transfer to L2) is an event with a non-zero probability of TBD% [RD 34].

ATHENA will therefore represent a space debris risk, both to the protected regions (GEO – 35785 ± 200km altitude, ±15° from the equatorial plane centred at the Earth; LEO – ≤2000km altitude) and also for re-entry. The ATHENA SC will be several tonnes in mass, and accordingly would definitely violate OR-07 from on uncontrolled re-entry should the SC return to Earth, even when multiplying the re-entry casualty risk by the Earth-return probability (in order to determine the true casualty-risk.)

Accordingly the ATHENA mission shall be required to perform an EoL disposal manoeuvre in order to reduce the probability of protected region or Earth-return to a more acceptable level. The strategy foreseen for ATHENA is currently identical to that proposed for

EUCLID, performing an insertion manoeuvre into a Jacobi-forbidden return exterior heliocentric trajectory as described in [RD 34] for the GAIA mission.

For this disposal an allocation of $10ms^{-1}$ TBC is made.

*Note: During the disposal period, the possibility still exists to perform science observations (particularly during the 90d period between DISP#1 and DISP#2), and it is anticipated that this will occur. However, we size the mission NoP and EoP assuming all required net observing times are contained within these phases (TBC).*

### 4.4.6.3 Passivation

**OR-05** in [RD 13] states passivation of a space system shall be completed within two months after the end of the operational phase.; this is in order to limit the probability of an explosive event once the mission is completed (i.e. to enter a passive state as soon as possible). The ATHENA SC shall therefore be required to passivate shortly after the disposal manoeuvre has been completed.

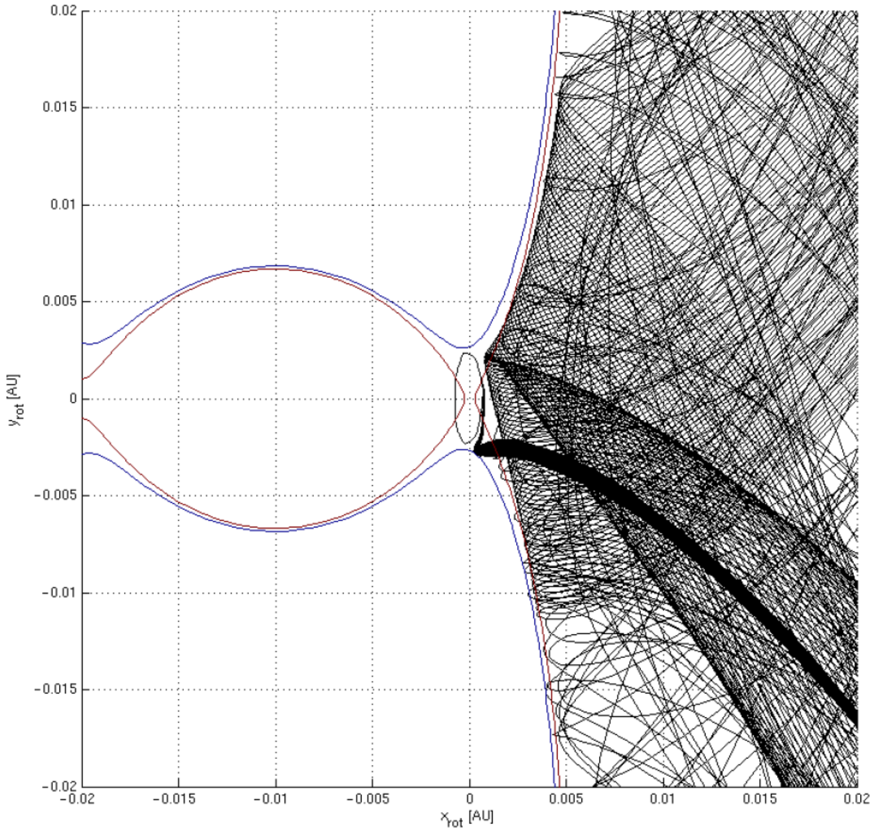


Figure 10: Relative trajectories in the ecliptic frame for Gaia after disposal for various departure dates between September 7th and September 17th, 2019. The trajectory is propagated for 100 a. Taken from [RD 34].

#### *4.4.6.4* Ground Support & Coverage

TBW.

#### *4.4.7 Post-Operations Phase (POP) and (AAP) – SGS only*

TBW.