Lessons in cat herding: methods used for managing a large international collaborative engineering project, the Ariel mission payload

Paul Eccleston, Rachel Drummond, Andrew Caldwell, Georgia Bishop, Lucile Desjonqueres, Alexander Davidson, Giovanna Tinetti, Salma Fahmy, Ludovic Puig, Jean-Christophe Salvignol

Published version information:

Citation: Paul Eccleston et al., Lessons in cat herding: methods used for managing a large international collaborative engineering project, the Ariel mission payload, Proceedings Volume 13099, Modeling, Systems Engineering, and Project Management for Astronomy XI; 130990H (2024)

DOI: https://doi.org/10.1117/12.3019819

Lessons in Cat Herding – methods used for managing a large international collaborative engineering project, the Ariel Mission Payload

Paul Eccleston *[a], Rachel Drummond [a], Andrew Caldwell [a], Georgia Bishop [a], Lucile Desjonqueres [a], Alex Davidson [a], Giovanna Tinetti [b], Salma Fahmy [c], Ludovic Puig [c], Jean-Christophe Salvignol [c]

[a] RAL Space, STFC – Rutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX, UK;

[b] University College London, Gower Street, London, WC1E 6BT, UK;

[c] ESA ESTEC, Keplerlaan 1, NL-2201 AZ Noordwijk, The Netherlands.

* corresponding author: paul.eccleston@stfc.ac.uk

ABSTRACT

The Ariel space mission will characterize spectroscopically the atmospheres of a large and diverse sample of hundreds of exoplanets.. Ariel is an ESA Medium class science mission (M4) with a spacecraft bus developed by industry under contract to ESA, and a Payload provided by a consortium of national funding agencies in ESA member states, plus contributions from NASA, the CSA and JAXA.

With the payload being provided by a consortium of scientific institutes and industrial partners funded through their respective European national funding agencies, and additional contributions provided by ESA, NASA, CSA and JAXA, the coordination and management of this team is vital to the successful delivery of the mission.

This paper will describe how we have tailored the standard systems engineering approaches taken for space instrumentation and implemented these in the large consortium structure. This has been done in order to try to maximise the efficiency of the consortium work and to allow as close to a seamless flow of information as possible. We outline the key tools being deployed by the payload management, systems engineering and product assurance teams in the consortium.

Keywords: Astronomy, Instrumentation, Consortium, Management, Systems Engineering

1. INTRODUCTION

The Ariel space mission will characterize spectroscopically the atmospheres of a large and diverse sample of hundreds of exoplanets. Through the study of targets with a wide range of planetary parameters (mass, density, equilibrium temperature) and host star types the origin for the diversity observed in known exoplanets will be better understood. Ariel is an ESA Medium class science mission (M4) with a spacecraft bus developed by industry under contract to ESA, and a Payload provided by a consortium of national funding agencies in ESA member states, plus contributions from NASA, the CSA and JAXA.

With the payload being provided by a consortium of scientific institutes and industrial partners funded through their respective European national funding agencies, and additional contributions provided by ESA, NASA, CSA and JAXA, the coordination and management of this team is vital to the successful delivery of the mission. With 17 ESA member states, plus the US, Canada and Japan, contributing a large degree of coordination and interface management is required. Through working together over the eight years of the project so far, and through the previous experience in the teams of working in such a consortium, many methodologies and techniques have been developed and iterated to allow robust yet pragmatic management of the organization.

Modeling, Systems Engineering, and Project Management for Astronomy XI,
edited by Sébastien Elias Egner, Scott Roberts, Proc. of SPIE Vol. 13099,
130990H · © 2024 SPIE · 0277-786X · doi: 10.1117/12.3019819

Mission & Payload Overview

Ariel is due for launch in 2029 on board an Ariane 6.2 in a dual launch configuration with the Comet Interceptor mission. It will operate from an orbit around the second Lagrange point of the Sun-Earth system (L2), which offers the benefit of a stable thermal environment thanks to the constrained relative orientation of the Sun and Earth to the spacecraft. The nominal mission lifetime is 4 years, however the mission will be sized to allow a lifetime extension to 6 years.

The spacecraft is composed of the Service Module (SVM), onto which the Payload Module (PLM) is integrated. The SVM hosts all the platform elements of the spacecraft such as the attitude and orbit control, power, data handling and communications systems, as well as warm electronics units and the cryocooler of the payload. The PLM hosts the telescope and detection chain of the payload, along with so-called “V-groove” structures, which serve to thermally decouple the PLM from the SVM. The S/C will be three-axis stabilized and oriented such that the PLM is maintained in the shadow of the SVM, enabling the telescope assembly to cool passively, reaching an operating temperature <70 K. The total spacecraft wet mass is approximately 1410kg with a power budget of 1kW.

The PLM holds the telescope assembly, containing an afocal off-axis Cassegrain telescope and common optics, which direct the incoming light to the two science instruments. The instruments consist of the Ariel IR Spectrometer (AIRS), providing spectroscopy over the wavelength range 1.95 - 7.80 μm and the Fine Guidance System (FGS) instrument which contains 3 photometric channels, VISPhot (0.50-0.60 μm); FGS1 (0.60-0.80 μm) and FGS2 (0.80-1.10 μm), as well as a low-resolution spectrometer covering the waveband 1.10-1.95 μm. The FGS1 and FGS2 channels also serve as a Fine Guidance Sensor in the attitude control loop of the spacecraft, allowing to achieve the pointing stability required to meet the science objectives.

The overall responsibility for the mission lies with ESA, with the Ariel Mission Consortium (AMC) being responsible for the PLM and warm payload units as well as for the IOSDC. The members of the AMC are nationally funded by their respective national agencies and the overall collaboration is governed by a Multi-Lateral Agreement (MLA) to which all agencies are signatories.

Further details of the mission and spacecraft SVM design can be found in Salvignol et al [1], while an overview of the design of the payload, telescopes and instruments can be found in Eccleston et al [2].

2. PROJECT MANAGEMENT STRUCTURES

Consortium work division

The Ariel Payload and IOSDC are, by design, modular. The modularity has been used to optimise the architecture of the payload for its scientific objectives, and to facilitate the division of work between the participating countries in a manner that keeps the international interfaces clean and as simple as possible. This reduces risk to the overall programme and enables the construction and test of sub-assemblies which require interaction between a smaller number of countries and institutes than are involved in the AMC as a whole.

The Consortium has distributed effort according to the skills and resources in the participating institutes and reflecting the areas of national interest in the science of Ariel. This also ensures that a broad spectrum of state-of-the-art and appropriate technical design expertise is brought to bear on the design, construction and test of the instrument. Details of the design and functional breakdown of the payload are contained in [1]. An overview of the division of work between the participating countries is shown in Figure 2-1 below.

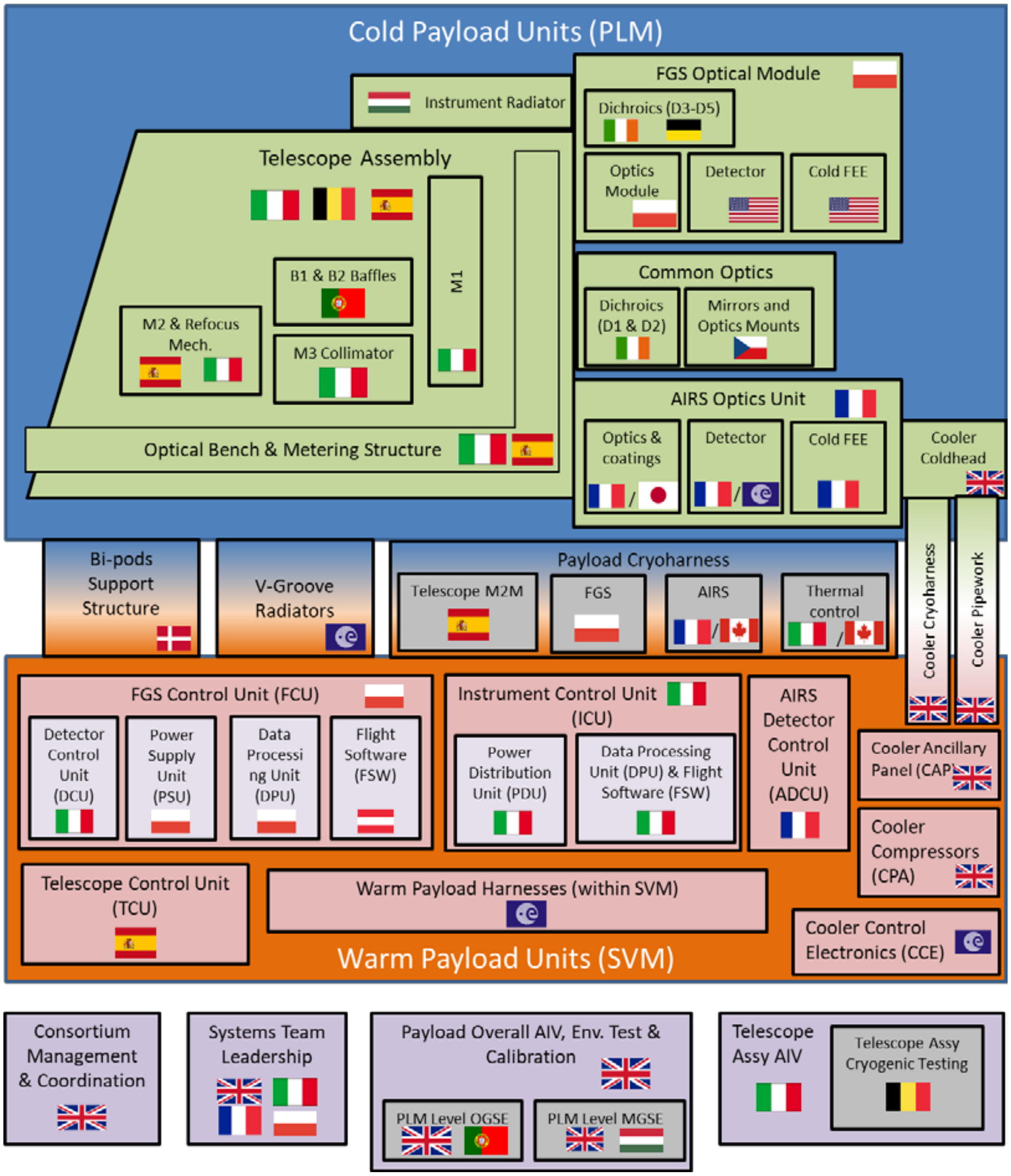

Figure 2-1: Overview of National Responsibilities

Internal AMC management

There is generally more than one institute involved within each nation. Each nation is organised as a subgroup with one or two Co-Principal Investigators (Co-PIs) leading and acting as the point of contact; however management at a working level will follow the matrix approach with the Consortium Project Manager having direct access to the work happening on a day-to-day basis via the National Project Managers.

The management structure is mirrored in each country to a greater or lesser extent depending on each country's involvement. Each country has design and management responsibility for a clearly defined sub-system or workpackage(s), as described above. The details of the methodologies for interface control in the internal sub-system interfaces (such as those within the telescope assembly) are documented in the Systems Engineering Plan which was developed in phase A and agreed to by all parties.

The responsibility for the work of the consortium formally rests with the Consortium PI and the Co-PIs, assisted by the Consortium Project Manager. In order to manage the work of the distributed consortium seven defined teams will assist the consortium management to coordinate the work. These are the Consortium Co-PIs Board, Consortium Management Team (CMT), the Consortium Science Coordination Group (CSCG) consisting of the leads of the Science Working Groups, the Consortium Systems Team (CST) (of which the Systems Core Team is a subset with specific responsibility for the payload level coordination), the Consortium Instrument Scientist Team (CIST), the Instrument Operations and Science Data Centre (IOSDC) Management Team and the PA Management Team.

Each committee or team has documented terms of reference which are drawn up and approved by the PI, CPM, and the head of the relevant group, to make absolutely clear and well-understood the tasks and responsibilities of each group.

Membership of the Ariel Mission Consortium is subject to rules as set out in the Consortium Constitution and Code of Conduct which is contained within the management plan which is approved by all of the Co-PIs.

During the adoption process a Multi-Lateral Agreement (MLA) between the funding agencies of the consortium and ESA has been drawn-up and approved. Part of this MLA includes the provision of a multi-national Ariel Steering Committee to provide agency level oversight of the activities of the consortium & ESA. This Steering Committee would be the ultimate arbiter when it comes to problems and issues that result in conflicts between the national interests of the consortium if they cannot be resolved by the Co-PIs Board, or any major programmatic perturbations outside the control of the consortium.

The membership of the AMC Steering Committee includes representatives of the funding agencies in all the countries that are party to the MLA, with the Consortium PI, the Consortium PM, the ESA Project Manager, ESA Project Scientist & ESA Prodex office Ariel lead all invited to attend. The Steering committee with elected a Chairperson from among the representatives of the major lead funding agencies (France, Italy, Poland, Spain & UK in alphabetical order) and a deputy-chairperson from among the other funding agencies at their first meeting, these positions then rotate on a term of 2 years. The ESA PM acts as the secretariat for the Steering Committee.

Particular strengths & currently identified weaknesses of management structure

Over the past approximately 7 years (since the start of the phase A studies of the M4 missions), a number of aspects of the management structures have evolved in response to feedback and evaluation of how well the project is organized. This is both through regular formal reviews of the management plans (for example at Mission Selection Review, System Requirements Review, Payload Preliminary Design Review etc.) but also through a regular check at our ~quarterly meetings of the Co-PI’s board.

The following aspects of the management structure have in particular been shown to be strengths of the scheme being followed.

- There is a positive relationship between the AMC and the representatives of the national agencies as represented on the Steering Committee. Through regular communication at both national level (between the Co-PIs, NPMs and the SC representatives) and at international level (through the AMC boards and the SC) there has been good syncronisation of the program and open dialogue throughout.
- The relationships between the AMC and the ESA appointed Ariel Science Team (AST) is also good. There is, of course, significant overlap in personnel between the consortium management and the AST as the leading scientists in the field are generally involved at senior level in both cases. However, there are also a number of independent community scientists (appointed by ESA through a call to which people in AMC leadership roles are not eligible) who play a valuable role in representing the wider scientific community and their interests in the mission.
- There is a good series of regular communication between the National Project Managers (NPMs) as detailed in chapter 4 below. This has not always been the case in other large instrument consortia and has shown to be effective in the past years in ensuring that there is a “heartbeat” on a cadence commensurate with the periods over which key management decisions need to be made to allow such a project to make the correct progress.
- There is a good and healthy separation of the strategic leadership function (as embodied by the Co-PIs Board) who are charged with taking the strategic view and the “tactical management” function (as embodied by the

Consortium Management Team). There is a clear and well documented set of responsibilities these separate bodies in the consortium management plan, and both work well in their area of responsibility.

- There is some very useful and necessary overlap between membership of the Consortium Co-PIs board, the Consortium Management Team, and the Consortium Systems Team by key individuals who are charged with ensuring the seamless flow of information between these bodies.

There are also a number of observations that have been made that demonstrate where there are some known weaknesses or difficulties in the chosen management structures. While steps have been attempted to remove or mitigate these, they remain in place and pose some challenges for the management of the project.

- There are differing levels of engagement from different members of the Consortium Management Team (specifically the NPMs). Largely these correlate with the fraction of time that the individuals have devoted to the execution of their respective parts of the Ariel project; the NPMs for most large contributions are full-time committed to Ariel (or close to this) while for some of the smaller contributions the NPMs might only be working on Ariel at the 20-40% FTE level. This can sometimes lead to difficulties in getting timely responses and high-quality management information input from all parties at a uniform quality.
- There are sometimes differences in the alignment of timescales and level of prioritization given to the relevant corners of the project management pyramid (cost-schedule-performance-quality) between different groups. This is due to differing external pressures for different teams – some may have very tight cost pressures which influence the approach to any particular problem while others may have a more relax financial envelope but be prioritizing maximization of performance at the price of schedule. Understanding and balancing these differences is a continuous task for the consortium central management and it is overly optimistic to believe that it would ever be possible to align these, instead we chose to discuss and recognize the differences.

3. CLARITY OF ROLES & RESPONSIBILITIES

Roles within the AMC

The formal strategic and programmatic management of the consortium is provided through the Co-PIs Board. This group, chaired by the PI, will consist of the lead scientists from each of the contributing partner countries, with a second representative from those countries with the largest scale contributions and the Consortium Project Manager. It interfaces with the ESA project team through the PI and CPM, and to the Consortium Management team through the CPM and interactions between the Co-PIs and their National Project Managers (NPMs). The Co-PIs Board meets in person at every consortium meeting, and at least quarterly throughout the project (either face-to-face or by video-/tele-con).

The functional project management of the consortium activities (as separate from the strategic direction given by the Co-PIs Board) is undertaken by the Consortium Management Team (CMT). This group, chaired by the Consortium Project Manager (CPM), consists mostly of the National Project Managers of each of the contributing countries, plus the consortium central technical and science leadership in the form of the lead systems engineer and instrument scientists. The relevant NPMs will interact with the ESA Prodex office, and the nominated Prodex lead for the project may also be invited to the CMT meetings where and when appropriate. The CMT will meet regularly in person and via Videocon at least monthly through the phase BCD of the project to ensure that problems and issues are addressed in a timely and constructive fashion.

The Consortium Systems Team (CST) is the group that will coordinate the technical activities of the payload development program. This group is chaired by the Consortium Engineering Manager and includes the technical lead (Systems Engineer or Engineering Manager) for each major deliverable system, plus the payload Systems Engineers and Instrument & Payload Scientists. The key members of the ESA project team who are responsible for contact with the AMC are invited to CST meetings. This multi-national team will stay in close contact throughout the design phase with regular face to face meetings (approximately every 3 months) and videocons (fortnightly) to report and review progress and address common issues such as interface definitions. This model has been successfully implemented on previous large IR instrumentation projects (JWST MIRI [3], Herschel SPIRE, Euclid) and is a proven efficient mechanism for managing and coordinating distributed working among a large consortium. Within the CST there is an additional subteam which is the Systems Core Team consisting of the systems engineers and discipline leads who are responsible for the coordination of the overall overarching payload design and development. This smaller team will also meet regularly (fortnightly by Videocon) to coordinate the systems aspects including external interfaces of the payload.

There will be a number of cross-cutting working groups defined in the consortium that will address interface issues and common design issues between the teams. Discipline specialist representatives from the instrument and subsystem teams will participate in these working groups (as relevant for each team), along with the relevant members from the Consortium Payload Systems Team. The currently operating working groups at AMC level cover Optical, Thermal, Mechanical, Electrical & Electronics, Calibration, Performance simulation & modelling, Product assurance and AIV. There are also working groups formed at mission level with representatives from ESA & the S/C Prime team involved – these are be convened by ESA and the AMC will participate in these with representatives from both the payload system team and relevant instrument & sub-system teams. These mission level working groups cover: EMC, Cleanliness & contamination, and AOCS / FGS interfaces, micro-vibration and pointing stability working groups.

The Instrument Scientist Team is responsible for implementing the flow-down of Ariel scientific requirements to instrument requirements and defining the detailed system and sub-system performance requirements. As members of and advisors to the Consortium Management Team they advise on the science impact of all design decisions, carrying out supporting analyses and trades as appropriate; they may also be consulted by the Co-PIs Board for a view on the scientific effects of any design trades or risks that are being considered.

The Instrument Operations and Science Data Centre (IOSDC) team will be a distributed team with contributions from many consortium partners. The IOSDC team is organised functionally with a number of internationally distributed teams for areas such as software, calibration, data processing algorithms, observations and scheduling, uplink etc. Further details can be found in Pearson et al [4].

It should be noted that the roles described here have not been static and unchanging through the project – they have had to evolve and become better defined through the period that the team has worked together. Partly the roles have evolved to fit the personnel involved in the project, but mostly they have been driven by the needs to have effective management of this large consortium. This has involved the need for some occasionally uncomfortable conversations on the part of the PI and CPM in order to have people define their roles appropriately and to prevent the wrong people having management responsibility for which they are not correctly positioned, experienced or capable.

The role of ESA

The European Space Agency (ESA) is a prominent organization with extensive expertise accrued over many years, employing highly specialized experts across various fields. Typically, interactions with industry partners are managed through formal written reports and progress meetings. While industry partners have adapted to this structured environment over time, scientific institutes often find it challenging.

ESA faces the task of supporting payload development to ensure timely delivery and high quality, meeting the scientific objectives of the Ariel mission. This must be achieved without causing delays due to excessive demands for detailed justifications or qualifications of the design, and without imposing burdensome reporting requirements. To build credibility with the Ariel Mission Consortium (AMC), the ESA Ariel project team has adopted the following strategies:

- Providing specialized expertise on topics such as materials, either suggested by ESA or requested by AMC, without being imposed.
- Offering access to ESA test facilities when equivalent resources are unavailable within AMC.
- Concentrating efforts on the most critical issues to account for limited manpower.
- Accepting only the most crucial data, with reduced detail on less risky topics.
- Minimizing communication and reporting to the essential minimum, using standardized templates.
- Utilizing consortium meetings as progress reporting sessions for all stakeholders (AMC and ESA) and keeping AMC informed about the overall mission progress to maintain high visibility and motivation.
- Favouring direct discussions over written reports.

- Understanding the specific environments and needs of each institute, whether technical or managerial.
- Building trust by openly sharing information to define the best system trade-offs, both technically and programmatically.
- Most importantly, maintaining a respectful and constructive attitude in all interactions.

The ESA project maintains a financial reserve to support the Ariel Mission Consortium (AMC) as needed, which can be used to facilitate purchases (e.g., EEE parts/LLIs), procure manpower support, or access test facilities. This supportive stance of the ESA team enhances their acceptance as a valuable partner.

ESA also provides the Centralized Procurement and Payment Authority (CPPA) to ensure the quality and timely delivery of EEE parts. This reduces the burden on the AMC and highlights ESA's positive contribution.

Funding issues raised by AMC members are typically addressed through the Steering Committee. This committee includes representatives from the funding agencies of all countries involved in the Multilateral Agreement (MLA), along with the Consortium Principal Investigator (PI), the Consortium Project Manager (PM), the ESA Project Manager, ESA Project Scientist, and the ESA Prodex Office. The Steering Committee provides agency-level oversight of both the consortium's and ESA's activities and acts as the ultimate decision-maker for conflicts arising from national interests within the consortium or significant programmatic issues beyond the consortium's control.

To enhance the focus and effectiveness of managing issues related to schedule, manpower, funding, and organization, smaller meetings are also organized. These involve representatives from only 2 to 3 countries and allow for more direct and open discussions, making the process more efficient.

ESA ensures the interface between the AMC and Industry, the prime contractor for the spacecraft, through several supportive measures for payload development. From the outset of the project, ESA organized co-engineering sessions over a period of six months to consolidate interface definitions and facilitate team familiarity. Industry performs system-level analyses that the AMC is unable to conduct and runs interface meetings, keeping detailed minutes and action items. Additionally, industry participates in payload reviews to cross-check interface matters and provides expertise on specific topics upon the AMC's request. ESA also requested flexibility on interface definitions until a later stage to allow more freedom in payload design and ease the development process.

4. COMMUNICATION METHODOLOGIES

Communication is key to maintaining syncronisation, control and insight into the project at all levels. With such a large team multiple communication routes, both formal and informal, are required to ensure that everyone has the necessary information to efficiently completely their tasks, and is well motivated to do so.

Some of the key methods used for formal communications are:

- Regular full consortium meetings held in-person (except during 2020-2022 when travel was not possible) – all members of scientific and technical teams working in the consortium are invited. They are usually structured as a ~4 day meeting with parallel technical working group and science working group sessions set around a central day of plenary progress presentations and discussion groups. The hosting of these meetings rotates around the consortium members who volunteer to host the meetings which now usually attract 150-200 attendees in person plus a number who join remotely. During the early phases of the project these meetings were held 4 times a year, this has gradually reduced to twice a year now following the payload PDR where the work of most teams is more internally focused;
- In-person meetings of the Systems Engineering team on regular basis in-between the full consortium meetings. This meant that during the early parts of the project when there was a lot of interface negotiations and iterations the teams would meet in person every 6-8 weeks (alternating at the full ACMs or the Systems Team meetings); now in phase B2/C/D these are required less regularly and the in person meetings are quarterly.

- Regular meetings of the working groups (WGs), both science WGs and technical WGs (see section 3 above) via Zoom, Webex, Teams or similar. In-person meetings are also used irregularly by the working groups when necessary.
- Mailing lists have been created and are hosted on the RAL space IT server. A directory of persons on each list (e.g. NPMs, systems engineers, PA specialists, thermal working group) is maintained on a central sharepoint and updated as needed when teams change. This means that people can use on address to contact all relevant persons (and those wanting to stay informed of issues) without needing to remember all the email addresses. It also provides an archive of messages sent. The sharepoint is a repository for sharing minutes of less formal meetings, sharing files to track actions, or ongoing work and share documents that are in iteration, since multi-person modification is possible.
- A monthly consortium newsletter is compiled and circulated to all consortium members. This includes sections on noteworthy progress, notification for upcoming meetings that may be of interest, a list of recently published papers related to Ariel, and an opportunity for people to advertise Ariel related vacancies including doctoral and post-doc opportunities.

Informal communications are also key to the interpersonal relationships that are vital for the smooth functioning of the project. There are multiple routes used for this, from regular phone calls and videocalls between key participants within the AMC and with ESA, to use of messaging systems such as WhatsApp & Teams. There is a clear understanding, documented in the project management plan, of when formal and informal communication routes need to be used; however, this is something that does need to be regularly checked on and some teams are often reminded that there needs to be full formal traceability of anything which can be construed to be a decision or direction between parties in the project.

The communications also depend on interpersonal relationships between the individuals involved. It has been observed that having occasional in-person meetings are vital to the construction and maintenance of these relationships; during the Covid period of travel restrictions in 2020-2022 where in person meetings were not possible there was a noticeable slow degradation in the quality of the remote meetings as the "communication capital" built up in the team was used. The inevitable churn of project personal and the expansion of the team as the project moved from study into implementation meant that a growing proportion of the team had never met each other. After the first consortium meetings back after Covid in Paris in June 2022 and in Bologna in October 2022 this capital was re-charged and communication definitely became easier again.

There is also some conscious effort made by the project leadership in the AMC and at ESA to ensure the quality, openness and honesty of communication between all parties. This was a decision taken early in the project and agreed to by all parties to share openly and honestly the status of problems and issues as people have seen past examples where a lack of this has caused unnecessary difficulties and loss of trust. This is modelled by the respective project leaders in their communications with each other, with the teams and with the whole consortium at the regular meetings.

5. SYSTEMS ENGINEERING MANAGEMENT

One of the key challenges identified early in the project was the coordination and syncronisation of many distributed teams having to work together to solve the technical challenges associated with building this challenging mission. The large number of parties, with differing (and sometime divergent) needs and motivations, makes the leadership management and coordination particularly difficult; at times it can feel like trying to shepherd an uncooperative group of individuals (the "cat herding" of the title). The best way to properly coordinate and technical teams is through a rigorous and coordinated application of systems engineering methodologies; some of the details of how this is done is contained in this section.

The Systems Engineering Management within the Ariel Mission Consortium is done in a distributed fashion by the Consortium Systems Team (CST), as shown in Figure 5-1.

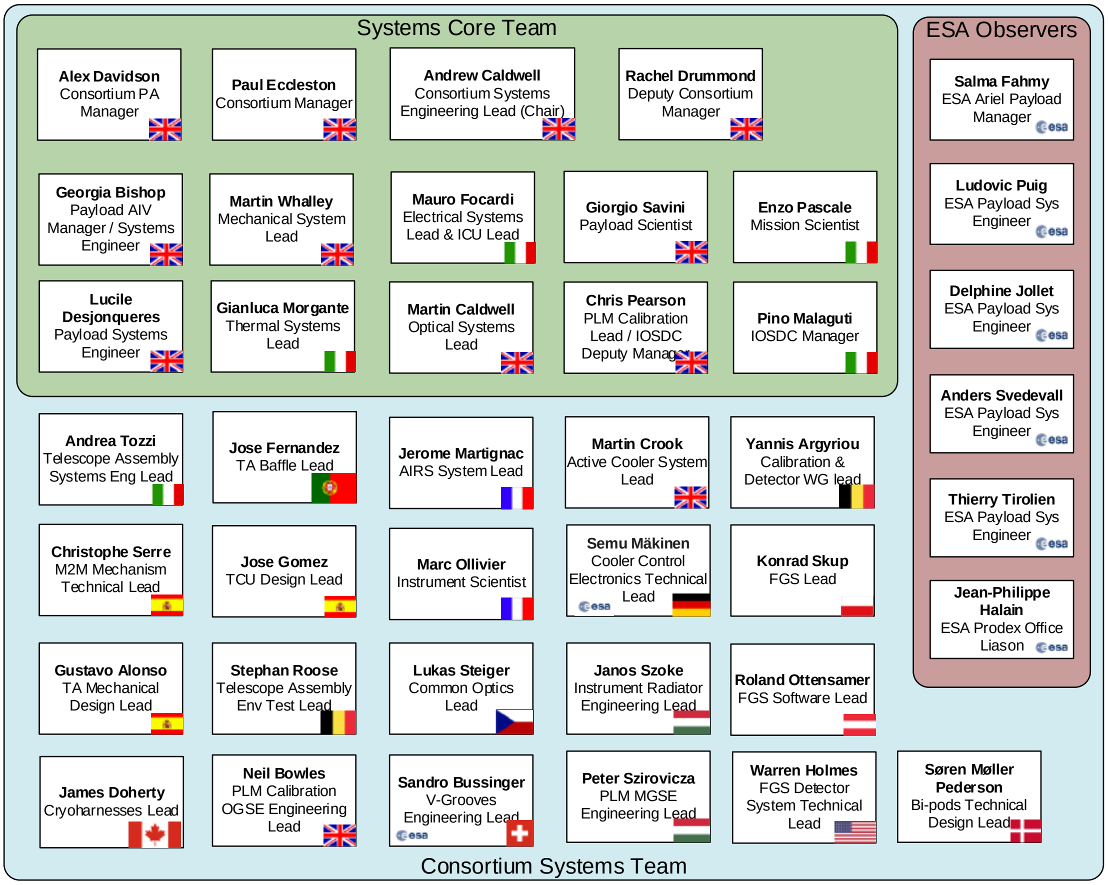

Figure 5-1: The Ariel Consortium Systems Team

The CST is comprised of the discipline leads within the Core Team, technical representatives from all of the instruments & subsystems, and the ESA project team. The CST meets on a regular basis (both virtually and in-person) and is supported by a number of dedicated working groups (e.g. Thermal, Mechanical, Optics, Calibration). In addition to the usual domain specific analyses activities (e.g. thermal modelling, finite element modelling, straylight modelling), the CST is also responsible for requirements engineering, verification, technical budget control, interface management, engineering data configuration control, and system level analyses, including impact analysis, reliability analysis, radiation modelling, and STOP analysis.

Requirements Management and Verification

The requirement management and verification activities for the Ariel payload are managed centrally through an IBM Rational DOORS© database. This database, shown in Figure 5-2, contains all of the requirements documents created and managed at Payload level, including the two main Payload level requirements documents, the Payload Requirements Document (PRD) and the Development Model and Ground Support Equipment (DMGSER) requirement document. It also contains the upper-level requirements documents between the mission elements, the Payload Interface Document (PID) and Payload Systems Requirement Specification (PSRS). Finally, it also includes the instrument and payload subsystem requirement documents (e.g. the Fine Guidance System, FGS, or the Telescope Assembly, TA). The relationships between the requirements within the different documents is managed through DOORS© 'links' to show the complete traceability between upper level requirements to lower level requirements. The scripting language within DOORS©, DXL, has been used to create a number of useful 'views' of requirements documents showing the upper and lower-level requirements with a red-lined comparison of the text, to easily check the flow down.

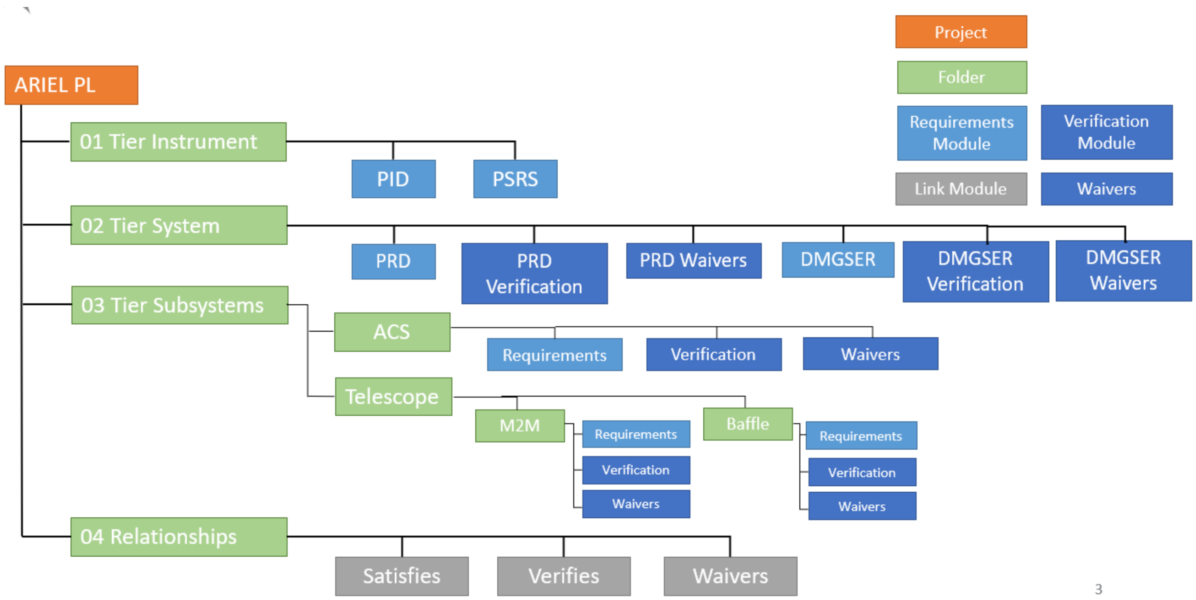

Figure 5-2: Ariel Payload DOORS© Requirement and Verification Database Structure

The DOORS© database is centrally hosted at one of the institutes, and it is not fully accessible to the whole CST. So spreadsheet versions of the requirements documents are maintained on the document management system, ECLIPSE©, to allow full visibility. While DOORS© does allow the import and export of spreadsheets in Microsoft Excel© format, it has a limited set of functionalities and can be sensitive to unexpected formatting or characters. Therefore, dedicated templates and scripts have been created to format and check the spreadsheet files before import and after export from the database. While full visibility of the requirements database to the entire CST would have been preferable, this has been a helpful tool in keeping the files in the document management system in line with the database.

In the initial phases of the project the requirements were managed in spreadsheets alone and a number of comments and revisions of requirements was kept only in the old versions of those files. Since the requirements were placed in the DOORS© database the full history of each requirement can be easily evaluated. Additionally, the Justification information for each requirement has been added to the database, either directly within the tool or with a reference to a supporting document.

From the beginning of the DOORS© database structure, it has been planned to use the same database to record and track the Verification of the requirements, from instrument and subsystem level, up to payload level, as shown in Figure 5-2. Separate DOORS© modules are used to maintain the requirements documents and the Verification Control Documents (VCDs), but the ‘link’ feature allows these documents to directly reference each other. A similar process to the requirements documents has been implemented to import and export the contents of the VCDs.

Interface Management

The management of the payload interfaces are divided into external and internal interfaces. The external interfaces are from the Payload Module (PLM), warm electronics units, and Active Cooler System (ACS) towards the Service Module (SVM) of the spacecraft. The external interfaces are formally managed by ESA. The internal interfaces, as shown in Figure 5-3, are between all of the payload instruments and subsystems that constitute the PLM. The internal interfaces are managed within the CST.

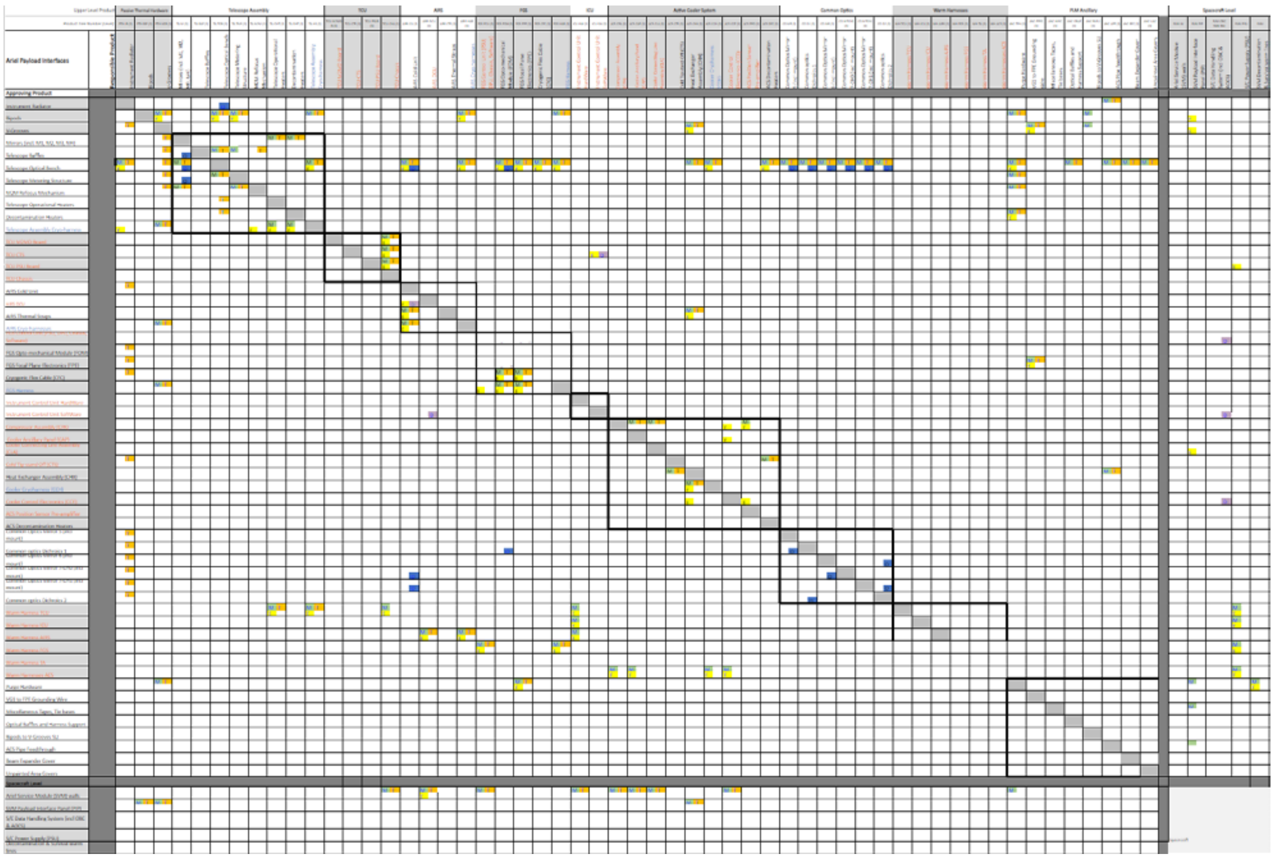

Figure 5-3: Ariel Payload internal interface matrix

Following the payload product tree, the internal interfaces are divided between mechanical, electrical, thermal, optical and data handling interfaces. In total there are 279 interfaces to be managed. The interface matrix, Figure 5-3, is a Microsoft Excel© file hosted on a Sharepoint© system accessible to the whole CST. The columns and rows of the matrix are used to represent which instrument or subsystem ‘owns’ or ‘approves’ each interface, to ensure the interfaces are well controlled. The matrix also contains links to a detailed section of the spreadsheet where comments/discussion can be captured and links to the Eclipse© document management system where the Interface Control Documents (ICDs) are formally managed and approved.

STOP Analysis

One of the key analysis activities for the Payload performance is the Structural, Thermal, Optical Performance (STOP) Analysis. As the Ariel Payload operates at ~ 60 K the thermo-elastic effects on the Telescope Assembly, Common Optics and the AIRS and FGS instruments is considerable and needs to be well controlled within the design to ensure the performance of the system in flight. This involves maintaining the separate high fidelity models, as shown in Figure 5-4, with strong configuration control and interoperability.

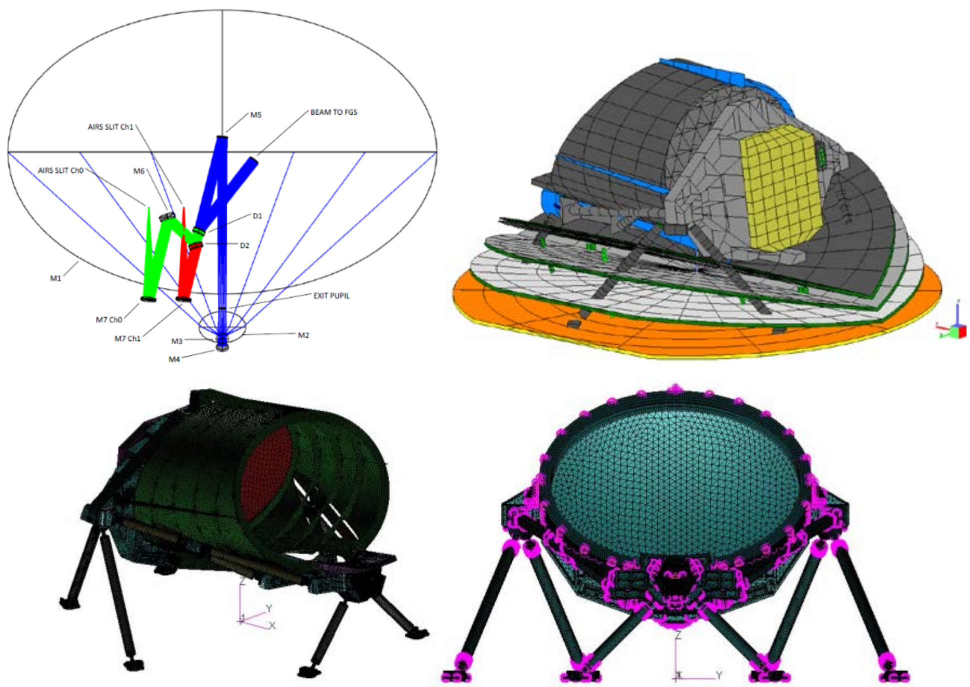

Figure 5-4: : Clockwise from top left: 1) Payload Optical Model, 2) Payload Thermal Model, 3) STOP FEM

The STOP Analysis for the two instruments, AIRS and FGS, are self-contained activities performed by the institutes responsible for each instruments. However, an added complexity to the Telescope and Common Optics STOP Analysis is that the different models and analysis activities are split up between different institutes within the Ariel Mission Consortium, as shown in Figure 5-5.

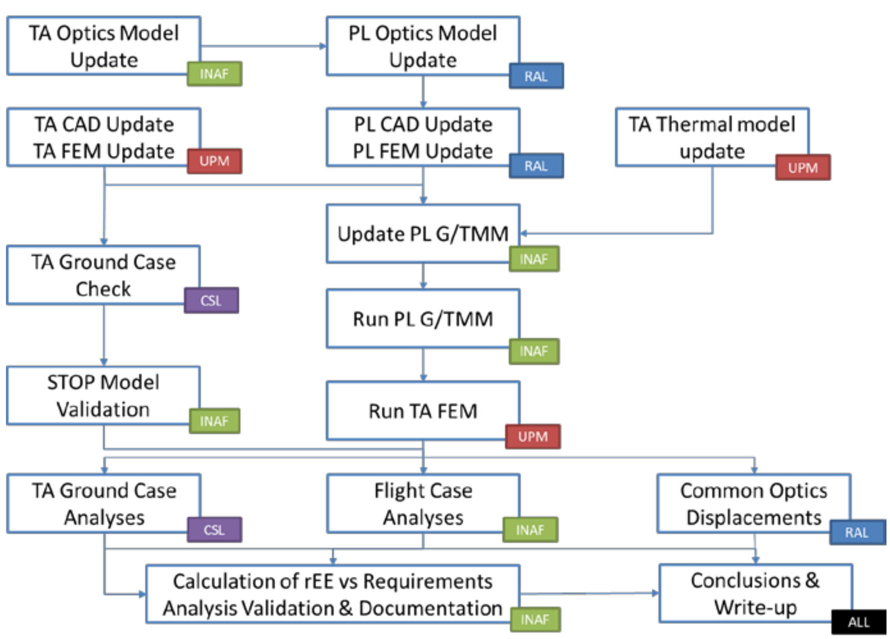

Figure 5-5: Ariel payload STOP analysis workflow

The splitting of responsibility between the teams and institutes has meant that there is a significant overhead in terms of configuration control and coordination. In the early stages of the analysis, significant effort was also needed to coordinate the exchange of results and to validate the analysis. As the ground and flight case analysis are the responsibility of different institutes, this also meant doing this work twice. However, as these two analyses have been compared against each other using predefined cases, this has also benefited in giving greater confidence in the overall results.

Mission Parameter Database

It has long been recognised that one of the key issues for keeping syncronised in this type of large project is to have a "single source of truth" for the key technical properties. This can then be used by all of the teams which need to use this type of information both for reporting and for modelling. This includes the teams responsible for the modelling of the payload scientific performance and preparing for the calibration activities.

The Ariel ESA-led Mission Parameter Database (MPDB) was set-up towards the end of 2022 and early 2023. It was first populated with an initial dataset of payload parameters provided by the AMC, representative of the payload design & analysis status at the time of the payload PDR (September 2022), transferred over from the historical AMC database (managed within GITHUB). This change of MPDB approach mainly emerged from the need to improve its configuration control and management structure.

In choosing a new tool, the team surveyed the different solutions used by previous ESA projects (Gaia, Euclid and PLATO) and studies (LISA) who already had a working MPDB. Several of these tools were bespoke developments tailored to the needs of the specific project and not directly adaptable for re-use on Ariel. The main exception was the PLATO project which used a commercial tool, COMET, a concurrent design API, freely available online in its default Community Edition. This tool was therefore also selected for the Ariel MPDB, enhanced by a dedicated contract with RHEA to enable concurrent access to COMET to many users simultaneously. In addition, a sFTP was also created to store all the large parameters contained within files that cannot be stored in COMET; instead, the sFTP links to each individual large file are stored in COMET to ensure all the necessary data can be extracted from a single convenient place. This was necessary given e.g. the spectroscopic nature of the Ariel AIRS and FGS instruments, with many wavelength dependent parameters (e.g. optical and detector properties).

Beyond the selection of the tool, the main lessons learnt retrieved from the discussions with the other projects was to not underestimate the work needed for the management of the MPDB, and avoid putting this burden on a single person who would likely become a bottleneck, slowing down the population of the database and its day-to-day maintenance, thus reducing its usefulness and preventing its deployment and wide-spread use across the AMC. To prevent this situation, a specific Configuration Control Board (CCB) management structure was designed for the Ariel MPDB, based on a delegated approach at subsystem level. Instead of a single person or a single team responsible for its management, the MPDB was split into the different subsystems that replicate the payload product tree, and the management of each subsystem was delegated to different independent subsystem CCB teams. Each team is comprised of 3 people, two from the AMC and one from the ESA project team. Jointly, these 3 people have the responsibility to manage the MPDB for their respective subsystem and organize themselves as they see fit to achieve this (e.g. which communication channels, frequency of meetings, roles between the 3 of them etc.). The two AMC members include one person from the relevant subsystem team (i.e. with the adequate knowledge to be able to efficiently gather and maintain the parameters pertinent to that subsystem) and one from the instrument scientists team (i.e. with the knowledge of which parameters are needed for the purpose of the mission level performance analyses). Finally, in addition to these subsystems CCBs, a general CCB that consists of the sum of all subsystem CCBs meets regularly on a quarterly basis, with the objective to coordinate on aspects that are relevant to all subsystems (e.g. common parameter structure needed across both instruments, need dates for database freeze ahead of the next cycle of performance analyses etc.).

This CCB structure has proven adequate so far, with the work ramping up by all teams now despite a slow start. A small learning curve was necessary at first to introduce and train all the subsystem CCB members to the Comet tool, but this software is sufficiently simple enough (as opposed to many other Model Based System Engineering Tools, which despite being very powerful, include so many functionalities that the learning curve is very step) that this initial learning period was rather short.

6. DOCUMENTATION MANAGEMENT LESSONS

Documentation management inside the AMC

The Ariel Consortium uses the Eclipse Documentation Configuration and Control Module in Eclipse (see https://www.eclipsesuite.com/products/#DCCM for details) to:

- Generate document references in a homogenous way;
- Add metadata to files to facilitate search functions;
- Review and approve files in a way that can be transferred when files are downloaded or copied to the ESA eclipse system;
- Create datapacks to show baselines, review snapshots and run reviews with RID and Action Item creation;
- Control access to different documents to the correct people, including ITAR controlled documentation and NDA covered information.

It is incredibly important to have one central document repository for the entire (large) consortium, where people can share draft documents and also find the latest approved, released version of a file, model or drawing. The metadata captures which institute created the document, what part of the project it concerns (instrument, payload, spacecraft, ground segment etc.) and what type of document it is. The database must be scalable and searchable in such a way as to support the documentation burden of such a large consortium. As an indication, as of June 2024 the Ariel ECLIPSE DCCM contains approximately 4000 documents, many of which have multiple historic issues and drafts; all can be easily searched.

Eclipse has proved to be fairly robust, if not always user friendly. It is certainly important to avoid emailing documents around which often leads to the wrong version being found by someone in the chain, or simultaneous updates needing to be merged. Access to all documents is centralized and available from any location (as long as this does not breach export control regulations).

Changes to the baseline configuration are captured in change requests and then in the document that requires change. These files can be linked to trace changes and why they were necessary. This is very useful in identifying when and why changes were made that may affect scope, cost, risk and schedule. Approvals by the concerned parties are captured in Eclipse. This change control process is subject to a strict workflow to ensure everyone is aware of the impact of the change before it is implemented.

The DCCM instance has been customized with specific document types and templates for Change Requests (CRs) and for Requests for Waiver or Deviation (RFW / RFD). These documents include additional metadata fields that have to be filled out concerning the requirements impacted (which can be across multiple requirements documents and levels), the levels of approval required and the status of these approvals. This allows tailored queries of the database to be constructed that allow easy definition of the requirement baseline (including approved but non-incorporated changes or approved deviations).

Documentation management outside of the AMC

In order to facilitate information exchange between the Ariel Mission Consortium, ESA and the Ariel S/C Prime Contractor, considerable thought was given to the means of synchronizing and ensuring consistency in the documentation management between each of these entities, who each have their own distinct documentation management systems. The ESA Ariel Project team, like the AMC, uses the Sapienza Eclipse DCCM tool, while the Airbus Ariel project is using PTC Windchill software. Several factors came into play in considering the approach, including robustness to errors, manageability, maintenance (including associated resources) overhead, timeliness of information exchange and adherence to document distribution regulations. Automated synchronization of each of the tools was neither technically feasible nor desirable due to the obligation for each entity to adhere to its own documentation management processes and guidelines. As such, a process involving manual intervention at some stage was unavoidable.

The ESA documentation system was the natural, and contractual, link for documentation exchange between all three parties. At one end of the range of solutions considered was thus to give access to a wide group of people from the AMC and industry to the ESA system, such that engineers could directly upload their documents to the ESA tool as well as retrieve documentation from it. While having the obvious advantage of being the most expedient method, it had several disadvantages which ultimately made this unfeasible. Apart from the overhead of maintaining access rights for external parties, the risk of erroneous or inconsistent maintenance of the tool was deemed too much of a risk, considering in particular the increasing number of documents with export control restrictions and the necessity to adhere strictly to these. Ultimately the process which has been adopted is a two-tier system in which documentation shared between the parties at working level makes use of a Microsoft Sharepoint repository provided to all parties by ESA, while the exchange of formally released and/or contractually binding documents is done through the official documentation management systems. The latter is performed by dedicated documentation management personnel who have access to the systems of the other organization, thus ensuring that each system is kept internally consistent and in line with the relevant organization's guidelines.

Overall, while documentation management tools have advanced in functionality over the years, it remains challenging to establish a system which enables a "single source of truth" documentation repository across organizations, which enables on the one hand flexibility and expediency as well as on the other hand being robust for configuration control and contractual purposes and compliant to export control regulations.

7. PRODUCT ASSURANCE MANAGEMENT LESSONS

Throughout this section, the role is referred to as Product Assurance, but this is known as Safety and Mission Assurance in NASA, CSA & JAXA led countries.

The diversity in the backgrounds Product Assurance Managers of the Consortium is hugely varied. This does not solely reference the experience levels but also the variety in culture of companies and organisations that are involved in the Ariel engineering Consortium.

To begin with, a more traditional way of managing all of the subsystem Product Assurance Managers (PAMs) was chosen and implemented. A formal working relationship was created and monthly Product Assurance working groups were held. However, it quickly became apparent that there was little-to-no engagement from the majority of the PAM's. In response to this, different and varied techniques for interacting with the PAMs in the Consortium have been developed and deployed to flex the approach to best manage the relationships with each party. There were some PAM's who responded better to the traditional style of working relationship with the Consortium PAM firmly in the 'customer' role. However, a much more positive and engaging response from some of the consortium PAMs has been found where we developed a highly collaborative and supportive working relationship.

Many of the organisations managing hardware deliveries did not have standardised templates. To prevent complications and confusion, the consortium central PA management function has issued a number of templates and guidance notes; their use is recommended rather than mandated. The reason for this is because there are some highly experienced companies and organisations delivering instruments or subsystems for Ariel who have established and detailed internal processes and templates and in order to prevent adding additional work. By taking this combined and flexible approach, it is ensured that the requirements and ECSS obligations are fulfilled while also lending support to some PAM's.

Another area which required further input from the Consortium PAM than had been expected was the other key roles from the instruments and subsystems. This is linked back to the where some of the organisations and personnel supporting the deliveries of Ariel have little recent experience of delivering into large institutional ESA missions with the full application of ECSS standards. For example, where teams may have delivered into programs such as Herschel & Planck 15-20 years ago, the application of PA standards expected by ESA is very different to what was applied then. With some of the academic based organisations delivering for Ariel, the role of Product Assurance was a relatively new and unknown element to them. It was originally laid out in the PA requirements that a PAM was necessary but not a detailed job description of what that role would entail (for the PAM or how the other key roles would interact with the

PAM). The AMC central management moved quickly to explain and inform the teams of what was required. In person, one-to-one conversations were held, and the expectations were laid out. Furthermore, in every Consortium Meeting, in the plenary sessions, there is a small section on Product Assurance which ensures that its importance is highlighted and kept at the forefront of everyone's mind.

The AMC PAM and central PA function continues to work in a diverse and varied way depending on the requirements of the PAM's working in the Consortium. This will continue to be an evolving methodology as well, as people leave and join the project as it progresses.

ACKNOWLEDGEMENTS

The Ariel Mission Consortium consists of institutes and industry partners in 17 ESA member states, plus the USA, Canada and Japan. The teams are funded by their respective national funding agencies.

The consortium management team at RAL Space and UCL are funded by a series of grants from the UK Space Agencies to conduct the work discussed in this paper.

REFERENCES

[1] Salvignol, J-C. et al, "The Ariel Mission: A mission of the European Space Agency for the characterization of exoplanets", SPIE Astronomical Telescopes and Instrumentation, Paper 13092-47 (2024).

[2] Eccleston, P. et al, "The Ariel payload design post-PDR", SPIE Astronomical Telescopes and Instrumentation, Paper 13092-47 (2024).

[3] Wright, D. et al, "System engineering and management in a large and diverse multinational consortium", Proceedings Volume 7017, Modeling, Systems Engineering, and Project Management for Astronomy III; 701708 (2008) https://doi.org/10.1117/12.787806.

[4] Pearson, C. et al, "The Ariel Instrument Operations Science and Data Centre: design, development and implementation", SPIE Astronomical Telescopes and Instrumentation, Paper 13092-269 (2024).