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Practical solutions for efficient & structured collaborative work in the frame of CALLISTO, reusable launcher first stage international demonstrator.

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Abstract

In order to address the technical difficulties and evaluate benefits of reusability of launchers, CNES, DLR and JAXA decided to join their efforts in developing a reduced scale in-flight demonstrator of a vertical take-off vertical landing first stage named CALLISTO (Cooperation Action Leading to Launcher Innovation in Stage Toss back Operations).
CALLISTO vehicle is roughly 13m high and 1.1m diameter, with a mass of roughly 3.5t at lift-off and propelled by a LOx-LH2 engine derived from Japanese Reusable Vehicle Experiment (RV-X). On top of technical brainteasers associated to bringing a launcher first stage safely back to ground, CALLISTO project has to tackle the extra challenge of cooperation across 3 continents & time zones (French Guiana, Europe, Japan), involving multiple cultures. The variety of cultures do not only relate to nationalities (mostly Japanese, German & French) but also to the background of the team members (researchers, engineers, project managers) and to the different "corporate cultures" of the entities involved (national agencies, laboratories, small & big industrial companies). After briefly summarizing the latest milestones & progress of CALLISTO, the paper will focus on practical solutions & processes that have been implemented for efficient & structured collaborative work within the team like shared System Engineering Database and Interface Control shared virtual spaces.

1. Introduction

CNES, DLR and JAXA are jointly developing a vertical take-off, vertical landing, experimental vehicle called CALLISTO (Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations). CALLISTO is a flight demonstrator for future reusable launcher stages that will lift-off from French Guiana at CSG, Europe's Spaceport for commercial launches. The target of the project is to develop all along the project, the skills and knowhow of the partners for future launchers recovery and reuse, it encompasses knowhow for product, vehicle and mission design as well as for ground segment and operation [1].

Major objectives assigned to the flight profiles of CALLISTO experimental vehicle are to demonstrate accuracy down to metric precision for flight profiles involving a boost-back manoeuver, a supersonic descent, as well as to demonstrate in-flight propellant management, and to experiment both soft and hard landing conditions.
Powered by an enhanced version of the RSR engine, a 50kN vacuum thrust class highly reusable and throttleable engine, derived from the one used by JAXA on RV-X experimental vehicle [2], CALLISTO vehicle is small: only 13m tall, 1.1m of diameter, <4t GLOM, 2.1t of which being LOX/LH2 propellants.

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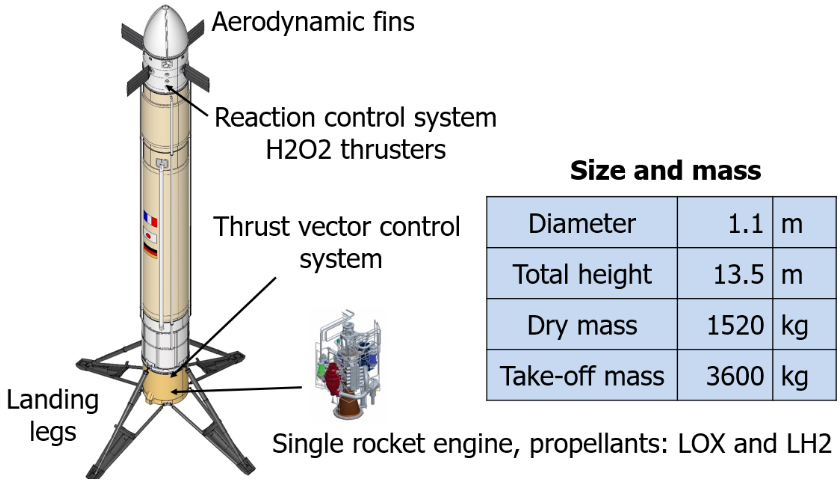

Size and mass		
Diameter	1.1	m
Total height	13.5	m
Dry mass	1520	kg
Take-off mass	3600	kg

Figure 1: CALLISTO configuration and dimensions (aerodynamic fins and landing legs are deployable)

With an ambitious target of up to 10 flights over a 6-month period starting in 2024, the project faces multiple challenges, of different natures.

There are of course, technical challenges associated to the novelty, for Europe and Japan, to bring a launcher first stage safely back to ground. Several new products, like for example deployable landing legs, propellant management devices, have to be developed and key technologies, Hybrid Navigation, Guidance and Control algorithms, as well as safety features, have to be matured [3].
Then, there are also system level technical challenges that are specific to reusability and return to launch site operations: in particular, but not only, aerothermodynamics conditions during return phases, mastering of vehicle internal environment in new flight domains and of course, post flight operations, as well as flight safety.

On top of these brainteasers, CALLISTO project has to tackle the extra challenge of cooperation across 3 continents & time zones (French Guiana, continental Europe, Japan), involving multiple cultures. The variety of cultures do not only relate to nationalities (mostly Japanese, German & French) but also to the background of the team members (researchers, engineers, project managers) and to the different "corporate cultures" of the involved entities (national agencies, laboratories, small & big industrial companies).

This paper will focus on this "extra challenge" and how it is handled in the project. It will elaborate in more details the background and constraints of the collaborative framework and then present practical solutions & processes that have been implemented to achieve efficient & structured collaborative work. Finally, some return of experience will be shared and some recommendations given.

2. The context: the need for efficient and structured collaborative work

2.1 Meet the CALLISTO team!

The core team of CALLISTO project spans over 3 times zones, and 13 different locations:

- 3 CNES centers, involving 3 directorates (Space Transportation, Technology & Digital, Guiana Space Center), on 2 time zones (UTC +1(winter) / 2 (summer) in continental France and UTC -3 in French Guiana),
- 6 different sites in Germany, involving 9 DLR institutes with 17 divisions,
- 4 JAXA centers in Japan, including engine test center of Kakuda and Noshiro test facility (time zone UTC + 9).

This core team counts roughly 170 members whose work is mostly interdependent due to work-sharing (as shown in §2.2 Work sharing). Efficient collaboration in between partners on a daily basis is a key to the project' success.

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Although differences in management style and working habits were obviously expected due to the weight of national cultures in Japan, Germany and France, CALLISTO's palette of workplace culture actually has a wide panel of shades due to the different backgrounds of the team members (researchers, engineers, project managers) as well as a diversity of "corporate cultures" including within each partner organization.

CNES, JAXA, DLR are the main stakeholders of CALISTO and are tied by a Trilateral Agreement but, on top of them, more than 115 related entities (universities and, labs, small or big, space and non-space industrial companies) are involved in CALLISTO via contracts or partnerships. This adds 5 more countries to the wider team list (Belgium, Switzerland, Ireland, Norway, United Kingdom). At some point in time, those entities need access to some CALLISTO data to perform their assigned tasks and/or to procure some data to the core team.

It is difficult to say exactly how many persons have handled and will handle CALLISTO data over time but it amounts to some hundreds, from different countries, cultures and backgrounds, who work for CALLISTO from "part-time for some weeks" to "full time over several years". In order for the project to run efficiently, the project's data management system has to be compatible with this wide range of users and use cases.

2.2 Work sharing

CALLISTO is a balanced partnership based on a Trilateral Agreement. The three parties involved are equally interested by the outcomes of the project, investing similar efforts and taking similar risks. There are no contracts involving funds exchange binding the three entities together. As a consequence, although the work breakdown structure of CALLISTO identifies a leading entity for the different high-level tasks, as shown in Figure 2, all major project decisions or vehicle configuration changes are extensively discussed within the trilateral team. A steering committee involving high-level managers of the three entities endorses or arbitrates the decisions whenever relevant.

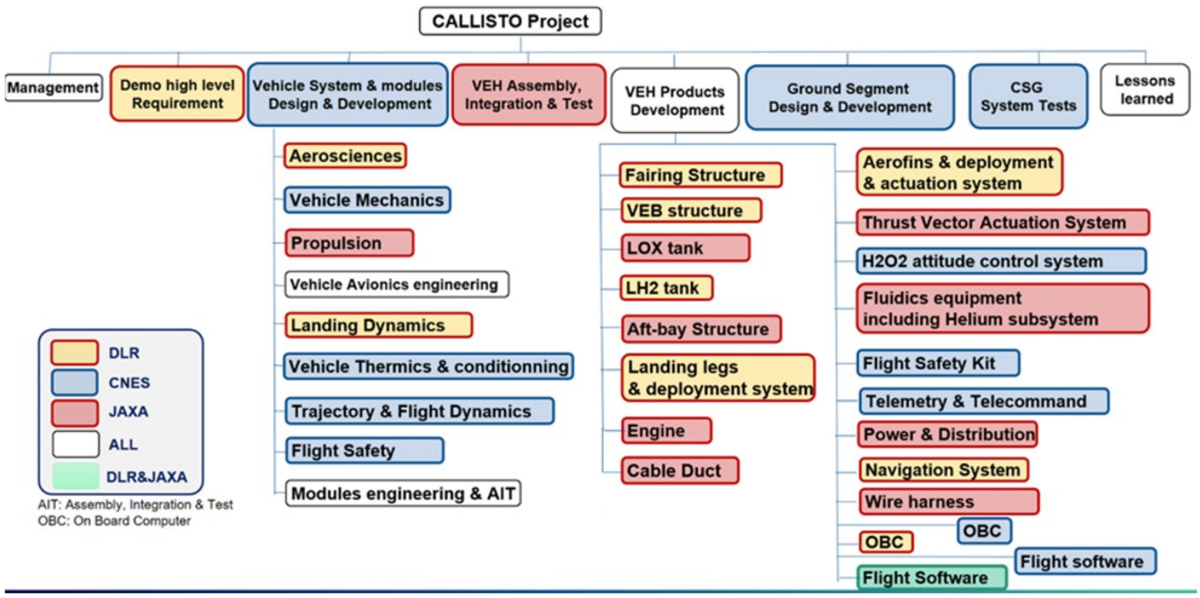

Figure 2: CALLISTO macroscopic work sharing focussed on vehicle and product design & development related tasks.

In order to balance the workload in between the teams, as well as to facilitate the exchanges on assembly operations, the notions of "modules" and "blocks" have been introduced.
A module is composed of a main load-carrying structure and a set of products that are accommodated on this structure. Modules are meant to be easily mounted/dismounted from one another.
The tasks of the module owner can be compared to the tasks performed by a "stage" owner in the Ariane launcher family. Those tasks are:

- to perform the engineering tasks to "accommodate" the different equipment on the main structure, not only in term of geometry (layout), but also in term of mechanical and thermal environment,

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- to procure all the necessary items like supporting structures (brackets & equipment plates), connecting elements and harness,
- to perform the module integration and testing activities,
- to verify module design compliance against its requirements & module flight model flightworthiness.

The CALLISTO vehicle has thus been "cut" into the following 5 modules, that can be clearly identified in the vehicle integration logic as per Figure 3:

- the Fairing Module (DLR) accommodates some navigation and safety kit elements,
- the VEB Module (CNES) accommodates the vehicle's brain (the OBC) along with the hybrid navigation box, two flight control actuators (H2O2 attitude control system and aerodynamic fins), along with batteries and telemetry/telecommand equipment as well as flight safety equipment,
- the LOx Tank Module (JAXA) and LH2 Tank Module (DLR with some tasks by JAXA) each accommodates a propulsion system controller, fluidics valves & pipes, as well as flight safety elements (pyrocords & harness hosted in the cable duct), the LOx tank module also accommodates some antennas,
- the Bottom Module (JAXA) accommodates the engine and its thrust vectoring system, the landing legs deployment system as well as batteries, propulsion controller and helium subsystem, and flight safety redundant equipment.

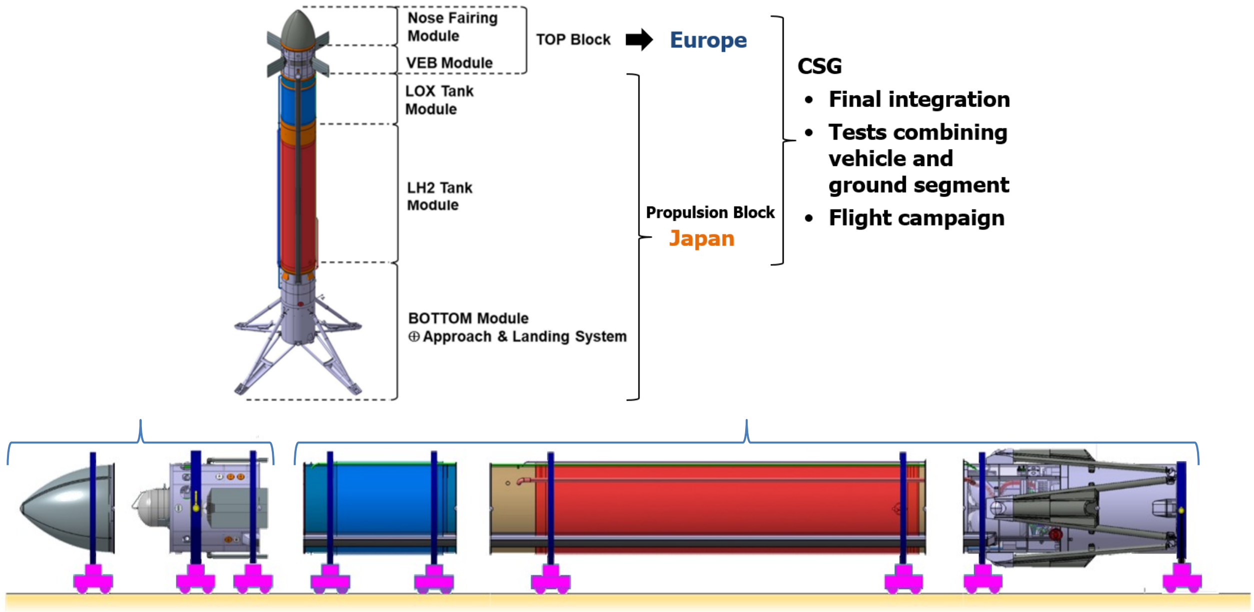

Figure 3: CALLISTO modules & blocks

The distribution of the vehicle into different modules has been done mostly to ease the management of physical interfaces between main structures and equipment that are actually in the perimeter of a single partner. For example, LOX tank module and bottom module mostly accommodate JAXA items and their main primary structures are also under JAXA's responsibility.

The vehicle system owner thus specifies to these different modules what matters "at vehicle level", like outer envelope of each module, mechanical & thermal loads to the module, mass, center of gravity and inertia of the whole module, and manages the inter-module physical interfaces.

2.3 This is where it gets tricky… ("that's life")

Europe already has the experience of developing Ariane and VEGA operational launch vehicle families, in a multinational context involving hundreds of companies and thousands of people across Europe and French Guiana. Comparatively, CALLISTO's reduced scale and its "experiment" tag, may lead to think that its development is rather simple. However, although it has no "payload" except for its own measurements, its overarching objectives are ambitious in terms of flight domain, accuracy and reliability (single vehicle with some development models & spare parts) given its tight schedule and costs constraints combined with the intrinsic challenges of reusability.

As the engine thrust is limited by the use of an almost off-the-shelf engine, mass optimisation is a key performance driver. The same is true for layout optimisation, since both inside layout (allowing to fit equipment in a small diameter) and outside protuberance are impacting the vehicle global aerodynamic performance.
Numerous trade-offs and iterations between system design in general (including CONOPS) and product design targeting low costs and/or use of COTS whenever possible, have been necessary to reach today's status [4]. Further evolutions will still occur until completion of product and vehicle critical design phases.
Although the project has not been explicitly applying agile methodologies, "real life" forced the project development process to be highly adaptive and flexible, given on the one hand the technical challenges, such as the ones described above, and the programmatic challenges on the other hand. Indeed, different decision milestones specific to each partner's internal processes were necessary for project funding or risk assessment. On top of that, contractual constraints between each entity and their industrial companies (also involving ESA in some specific cases) have an impact on the project. COTS procurement can also be challenging in the economic situation after the COVID-19 pandemic. On the whole, for both technical and programmatic reasons, several evolutions of CALLISTO system (vehicle and ground segment) were responsively implemented since vehicle preliminary design review.

In the above described context, where changes are unavoidable, project management processes and tools have to be set up to ensure good team communication and secure the management of engineering data, interface data, and the vehicle configuration. The driving principle of the different processes are:

- to allow quick, smooth & reliable data sharing between product owners and system design in a way that facilitates design & verification iterations,
- to keep vehicle configuration under control so it limits risks of missing important cross-impact or "side effect" of design changes, without delaying the project.

That would be the primary functions of the project management processes & tools. But CALLISTO has to live with some demanding practical constraints:

- national export control regulations limit the perimeter and the means of data exchange (e.g. CALLISTO technical data exchange by regular non-encrypted email between partners is forbidden),
- each entity IT constraints & habits (e.g. different operating systems and web browser, different web-conferencing tools, different technical tools like NASTRAN vs ANSYS),
- only a few hours per day offer meeting slots compatible between Japan and Continental Europe during regular working hours (8h-11h in Europe corresponds to 16h-19h in Japan during winter time). No meeting slot on regular working hours exists between Japan and French Guiana (12h difference all year long). It also means no regular common coffee break nor frequent informal conversations, that are sometimes key to discover or solve issues [5],
- large in-person meetings are limited by travel expenses and, in the past two years, by COVID-19 pandemic,
- only a part of the team members works full time on CALLISTO, so the common management process and tools have to remain light and understandable, but also as "universal" as possible to secure their enforcement by every team member while limit learning curve effect or the need of specific training.

3. How we manage it so far

3.1 Overview

First of all, regular meetings have been set-up to ensure "live" exchange on major topics:

- A short (1h) weekly slot is booked all year long on a fixed day & hour in all the core team member agenda for technical discussion. The meeting agenda is usually decided from 15 days ahead, for example to report a specific topic's progress to the team, to roughly 48h to 24h before to address "hot" or time critical topics. With only part of the team member working full time of the project, this "ritual" was helpful to start discussion and plan resolution of technical hurdles,
- Before the COVID-19 pandemic, large "in-person" trilateral team workshop every trimester, alternating between Europe and Japan, where usually extremely proficient times for project's progress and team spirits. Due to duration of the workshops, usually limited to 4-5 days so far, the planning of the plenary and splinter discussions (up to 40 meetings) requires a significant effort in order to ensure the participation of relevant key persons to splinters where their participation is needed. Since the beginning of the COVID crisis, only one large in-person trilateral workshop took place. Some punctual long meetings outside of regular working hours have been set to try to alleviate the lack of workshops in the meantime.

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Each of the European entities (CNES and DLR) have “detached” a CALLISTO team member in Japan, embedded in the JAXA team. These persons play a key role in mutual understanding of the technical & programmatic issues as they are able to share an “insider’s view” from both sides when a hot topics meeting appears. They are also able to create a space for informal exchange, which is almost impossible otherwise due to the different time zones. Informal exchanges, is a key risk reduction factor [5] as it allows early detection and mitigation of both programmatic and technical issues.

A collaborative online workspace named GALAXI, based on Microsoft SharePoint, where team members can co-edit regular Word, Excel or PowerPoint documents and share all type of files has been set up. During the course of the project, IT evolution of the hosting partner’s lead to an upgrade of this file sharing system. In the system used from 2017 to 2020, documents where organised by folders. The system upgrade was the occasion to switch to a classification of files by metadata instead of folders. This point is further developed in §4.
With the project growing and progressing from phase A to the transition from phase B to C, involvement of contracted industrial entities lead to the need to create several parallel collaborative workspace on this platform in order to manage access rights in line with intellectual property protection. Ensuring a “single source of truth” in this context for documents shared on different parallel workspaces, while still allowing “part time users” to easily find documents, became more complex.

As explained in §2.3, export regulation strongly limits the exchange of technical data by regular email. So, from the very beginning of the project, redaction of formal documents with a reference identification and number dubbed “Engineering Coordination Memo” (ECM) uploaded on the collaborative work space (and then emailing only the link to the recipients) has always been the way to have a quick written technical discussion between partners on CALLISTO. What looked like a complicated process at first sight, is now rather considered as an asset for traceability and capitalization of the technical exchanges. The key to its success is that the identification/numbering rule is easy and can be directly set by the author and that no signature process is needed.

In parallel of the “common work area” of the files sharing system, three topic-specific workspaces have been set up:
- One dedicated to the system engineering data base,
- One dedicated to interface management,
- One dedicated to requirements.

Compared to the “common work area” where all the (other) collaborative and reference documents are hosted, they have specific metadata and access rights. The System Engineering Data Base (SEDB) management and the Interface management are developed in §3.2 and §3.3. The space dedicated to requirements hosts Excel files that are annexes referred to in the Technical Requirement Specifications (TRS) documents. These Excel files carry the requirement quantitative data that may still evolve during the project while the requirement corpus and wording are in the TRS core document. Requirement traceability is managed with the commercial tool REQTIFY [13]. This combination of means allows fast implementation of Engineering Change Requests (see configuration management process in §3.4) while using only tools with a low entry barrier. Having the quantitative data in an Excel format also eases machine readability of requirement data.

Those file systems support the configuration management process that is described in §3.4.

3.2 System engineering database

Data and models are the fuel for engineers when development phase is on-going. Regardless of the tools, time and expertise that they have at their disposal, the usability and relevance of results obtained by engineering studies can be questioned if the inputs data are poorly managed. Engineering data management has been a central preoccupation from the very early phases of the project and a first version of a Systems Engineering DataBase (SEDB) was set in 2018, soon after the system requirement review (SRR) completion in order to:
- secure consistency of technical data,
- organize and ease data exchange between and within partners,
- ensure traceability of system studies inputs,
- have all technical data available in a dedicated space for system studies.
- set a format for data exchange

“System studies” stand for “System design analysis studies” and refer to inter-related evaluation, computations or simulations that allow to generate data for vehicle and product sizing that are consistent with objectives detailed in Mission Requirement Document and System Requirement Document. They include especially:
- mission analysis, trajectories and flight safety,

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- flight management & Guidance Navigation & Control: evaluation, analysis, simulations of navigation, guidance and flying qualities plus associated algorithms, vehicle management during flight, flight time line definition and tuning,
- transient phases (e.g. unfolding sequences of deployable items, lift-off/ landing),
- aerosciences engineering: aeroshape design, aerodynamics analysis, aerothermodynamics analysis,
- mechanical engineering: natural environment analysis, static and dynamics (i.e. vibrations), load evaluation (environment and induced sourced), acoustics, definition of vehicle bending modes,
- thermal engineering: heat rates and loads evaluation (environment and induced sourced),
- electrical engineering: EMC evaluations, radio-frequency visibility, power and energy budget,
- rocket propulsion analysis: thermodynamics behavior inside propellant tanks and fluidics system, POGO analysis
- internal and external vehicle lay-out,
- internal volume conditioning, etc…

These studies follow an iterative process (“closed-loop”) with product design until satisfactory convergence between product specification and product design is achieved while complying with high-level project objectives defined in the Mission and System requirement documents.

There was no engineering database commercial tool that had been previously experienced satisfactorily by all partners, and, being at the early stage of the project with limited staff on a full-time basis, the number one criterion for building this database was to use tools with low entry barriers, needing no specific training.
At that time, Excel was still widely used for data management [6] including in other European space projects. It was thus selected as a basis of CALLISTO engineering data management process, in particular because it allows embedding practically all human readable and machine-readable file formats as “objects”.
Figure 4 shows the template of SEDB data sheets issue page. Then several templates have been established for standardising the “data” sheet (for example for trajectory data, or product mass breakdowns) in order to allow easier treatment by automated tools.

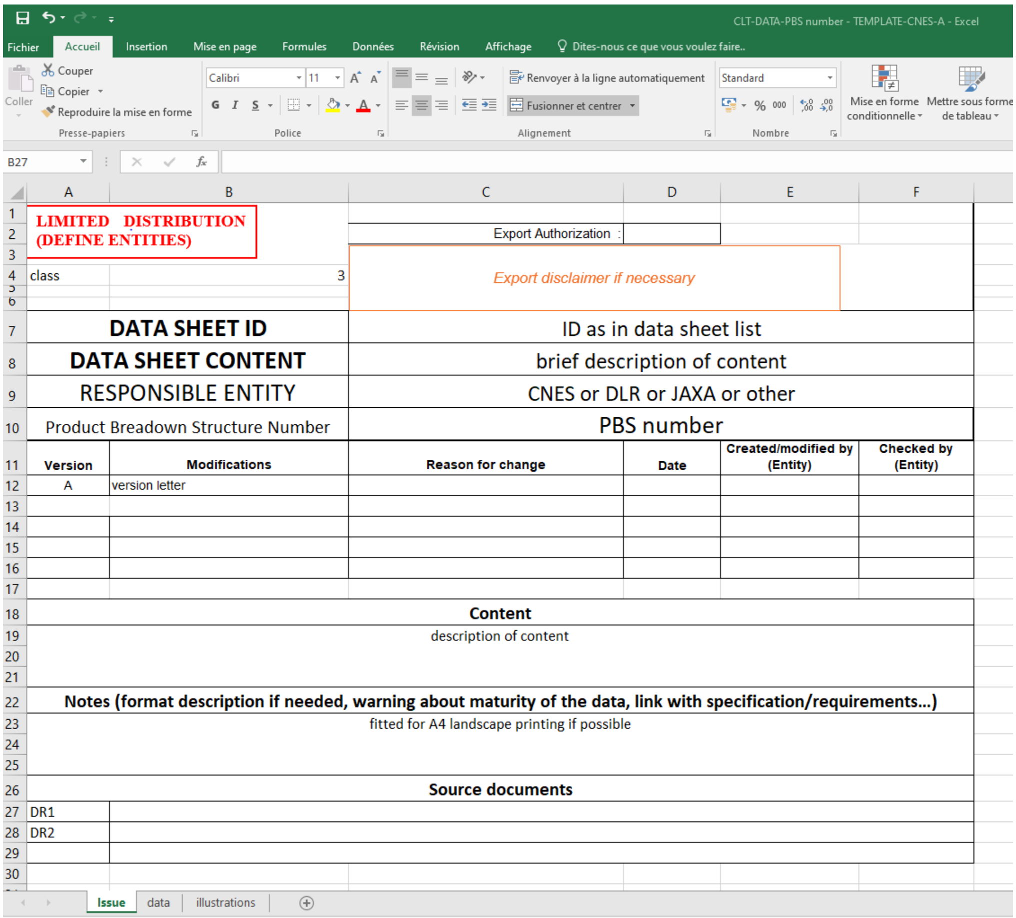

Figure 4: Generic template for SEDB datasheets.

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A process has been set up to manage the workflow of datasheets, from their elaboration by data provider to their effective use. This process involves the provider, the system architects and the end users as well as Quality Assurance. Datasheets can be either shared and discussed in a draft version (status = draft) or directly submitted to a checking process (status = pending check) in “SEDB Work in Progress zone”. A first “quality check” is then performed by the SEDB management (technical consistency team) to ensure template application and traceability of evolutions, as well as status with respect to expected vehicle or product configuration. Then, especially for a first version, data end-users are asked to check the usability of the data or model. Once data/model is deemed usable, the datasheet is moved to the relevant SEDB version as “ready to use”. Given the rhythm of CALLISTO development and quick design iterations, data can be short-lived, the level of data maturity can differ between products, and the formalisation of updated data is not always immediate. That is why, before performing a system study, the process requires that the list of data sheets that the engineer who will perform the study plans to use is validated by the vehicle architect and system consistency architect in order to confirm that the data are the latest and most appropriate for the planned study.

The scope and organisation of the files hosted in the database has evolved following the different design iterations between mission, vehicle design and product design. Today, the SEDB is in its 4th version. The first version of phase A was only a handful of datasheets, mainly related to aerodynamics, engine performance and trajectory data. The following versions contain around a hundred of datasheets each and are classified by their scope:

- mission data (mostly trajectory data),
- environment data (wind database, thermal flux data),
- vehicle data (vehicle main functional architecture schematics, Geometry, Mass, Centering, Inertia, Digital Mock-up, vehicle Finite Element Model, Aerodynamic Database, sloshing models, vehicle budgets),
- product data (product mass breakdown, CAD files, Finite Element Models, power consumption/dissipation models, thermal & mechanical properties, engine performance model, measurement plan),
- data related to ground phases operations like ground segment fluidics schematics & pressure losses,…

Apart from the SEDB, another major information for engineering lies in the coordinate systems and conventions. In order to comply to ECSS [7], references frames, and associated transformation chains formulas and time references were moved to a dedicated document that is now frozen except for vehicle design dependant data for which SEDB is referred to as the single source of truth. While building this document, partners noticed different conventions regarding of rotation axis that pitch and yaw refer to between France on one hand and DLR and JAXA on the other hand. Common conventions have therefore been set up in place in order to avoid errors.

Rotation angle	Convention DLR/JAXA	Convention CNES	Common Convention
Rotation around $z_A \equiv z'$	Ψ (yaw)	Θ (pitch)	eA_z1
Rotation around $y' \equiv y''$	Θ (pitch)	Ψ (yaw)	eA_y2
Rotation around $x'' \equiv x_B$	Φ (roll)	Φ (roll)	eA_x3

Figure 5: Common naming convention for rotations (x refers the longitudinal axis of the vehicle)

3.3 Interface management

Consistent interface management is known to be a crucial part of successful space missions [8], as ambiguous interfaces descriptions, which may cause (too) late changes of an interface design, bear significant risk of schedule and cost-overrun of the full project. Therefore, common standards like ECSS are defining sets of interface documents to ensure the clear specification of interfaces [9]. Particularly, the Interface Control Documents (ICDs) are providing design commitments between different subsystems, and moreover between the different teams designing these subsystems.

In the past different habits have emerged at the institutions involved in CALLISTO regarding how to efficiently implement an interface control process. The main difference that could be observed was whether the documentation should be focused on interface-centric or system-centric ICDs. A comparison of these two perspectives is given in Figure 6, whereas the later perspective is also known as Interface Description Document (IDD) or single-end ICD [9].

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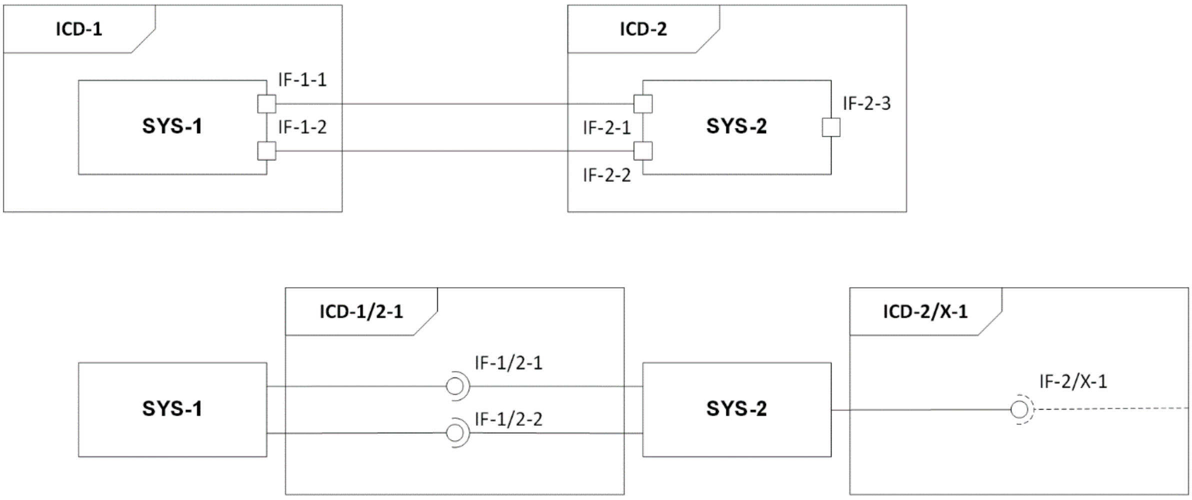

Figure 6: Comparison of the perspective of system centric ICD (upper) vs interface centric ICD (lower)

For CALLISTO it has been decided to implement interface-centric ICDs, mostly to support consistent interface definitions across different teams and institutions. However, some design details have been moved to annex files, such as mechanical drawings, electrical connector definitions and software protocol specifications, which follow a system-centric approach. This way it was possible to reuse specifications across several common interface types and to improve the machine readability of information, particularly for harness and avionics network design.

To increase the agility of the development cycle, the different interface specifications of a subsystem have not been aggregated into one single monolithic ICD, as it may be known to other space projects. Instead, lightweight ICD templates have been defined to specify each single connection between two subsystems as a self-standing document. This way asynchronous development of interfaces has been made possible, since not all interfaces of a subsystem need to be frozen at the same point in time. In practice it has been observed, that only few critical interfaces needed to be frozen early, to meet contractual or manufacturing constraints, whereas for other interfaces a quite late freeze would be acceptable, as they are far off any critical path. The disadvantage of lightweight vs. monolithic ICDs is that less descriptive context information can be given for potential reviewer of the documents. However, in CALLISTO we could see that this context is already sufficiently provided by so-called Product Files, a merged and tailored version of common Design Definition Files [10], Development Logic and Verification Plans [11].

Similar to the SEDB management process described in chapter 3.2, over 400 ICDs are currently managed on the joint collaboration platform GALAXI. Here, each ICD is jointly issued by (at least) three parties: the two subsystem providers responsible for each interface end, and the overarching system- or module-responsible to validate the assembled interface. Observations have been made that in most cases one of these three parties is the driver of the interface design, while the other two parties contribute with implementation details. Therefore, it has been explicitly allowed that all involved parties can create and edit ICDs, disregarding their role in context of an ICD, to support priority-based work allocation for the different teams. Joint concurrent editing of documents enabled by the GALAXI platform strongly supports this collaborative workflow.

Once the content of an ICD is agreed and signed by all involved parties, the document enters the "frozen" state, so that the teams can rely on the interface specification to initiate costly development and manufacturing processes. For a frozen ICD changes are only allowed via the configuration management process, as described in chapter 3.4. This process tries to avoid unnoticed design changes with a potentially high cross-impact on other systems.

3.4 Configuration management

A common configuration management approach has been defined by CALLISTO partners based on their respective experiences for the configuration management of space projects. Applicable provisions have been jointly discussed and defined for being easily understood and implementable by the partners with different cultures, uses and habits. They have the objective of matching CALLISTO project particularities and specific needs: one of the major characteristics of the CALLISTO project is indeed to have a single vehicle to be reused for several flights and, consequently, not to have a recurrent production to be configuration controlled. Consequently, special effort is put on the development phases rather than on the recurrent production phase, which is not foreseen for CALLISTO project.

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The global configuration management strategy has been defined for managing the configuration of the products and models in a controlled and traceable manner throughout the project life cycle. It starts with the identification of a quite simple set of documents to be monitored for a clear knowledge of:

- the applicable requirements from system to product levels,
- the design from the as-designed to the as-built status,
- the operational documentation.

The perimeter of documents to be configuration controlled is foreseen to evolve in a progressive way along the project main phases. The go-for-configuration-control milestone of each document has been commonly agreed starting from system PDR to system QR, including product PDR, CDR and delivery KP.

Adapted configuration and Quality processes are also defined for the management of the changes. A change is to be understood as an evolution of the configuration of a controlled product or of a controlled document, respectively after the formal approval of its configuration baseline or after the formal approval of the document. All changes are supported by Engineering Change Requests (ECR) thought to be the support form collecting the information that formally defines the change proposal versus the applicable reference: it is the support to document the change with dedicated analysis and technical justification named instruction. For an easy and efficient management process, ECRs are classified in 2 classes depending on the impact they may have on the design of the vehicle system or on its components. As a short summary, an ECR is classified in Class 1 when potentially impacting system performance and mission, so in detail, safety, high level requirements, interfaces, performance, databases and product breakdown. Consequently, an ECR is classified in Class 2 when not impacting system performance and mission but when it only impacts the product itself without external interaction. The authorization for instruction and the approval of each ECR are devoted to configuration change boards, being local or trilateral depending on the ECR class for gaining efficiency.

Finally, special focus has been made on the common definition of applicable rules for the identification of all products; such identification logic and relevant rules are based on past experiences of all agencies slightly adapted for a better common understanding and implementation. Product items are identified to guarantee their traceability throughout the project life cycle with special caution on the models during the development process.

Such configuration rules for the identification of products and for the management of the changes have been defined by trilateral working groups after many interesting exchanges and implementation loops though relevant sessions; they are applicable to all partners of the project and are to be cascaded towards their suppliers when needed. They are applicable for CALLISTO vehicle and ground segment for agreed controlled products and are compiled within a trilateral configuration management plan gathering and detailing all above mentioned points.

One of the challenges in the elaboration and execution of this process is to find the appropriate balance between rigor and reactivity. Rigorously identifying and assessing the impacts of configuration changes is mandatory to reduce the risk of failure in the context of a single vehicle approach like CALLISTO. However, documenting the justification and impact analysis of the changes, takes time and the planning may not always be compatible with waiting for complete instruction of a change (impact analysis, justification of acceptability, documentation) before effectively implementing it.
The balance is done via the choice of documents that are configuration controlled and in the structure of the ECR form. For example, in phase B and C, the documents that carry the configuration baseline at vehicle level are a selection of SEDB Excel files (see §3.2) instead of traditional detailed vehicle definition file. The ECR form is a one pager giving the rationale and description of the change and links to documents (minutes of meetings, memos, configuration-controlled documents or other documents that contributed to the impact identification, analysis and implementation).
On top of that, a dashboard allows to visualize on a single page all the ECR and their statuses and providing links to ECR themselves and to the different system configuration board minutes of meetings.

4. What if we started again?

Based on our lessons learned, several possibilities for improvement of the collaborative development process could be identified. While smaller improvements have continuously been implemented within the ongoing CALLISTO project, larger improvements would be more suitable to be considered for the start of new space projects. This way CALLISTO serves not only as a technical pathfinder, but also as a prototype for a transnational, collaborative and digitalized development process for future launch systems. The intention of this chapter is to share this experience in order to support the initiation of new projects.

Generally, most processes and structures described in chapter 3 have shown their effectiveness under “real-life” conditions within the technical and programmatic boundaries of CALLISTO. Therefore, the adaption of the before

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mentioned processes, or parts thereof, to similar development projects is suitable and already promoted within CNES, DLR & JAXA. In some cases the actual interactions between software, personal and organization could not fully realize the intended processes, due to user habits and heritage, scaling effects and technical limitations, or legal and programmatic constraints. These observed cases are the main source for future improvements.

So far, the design of the collaborative work environments and processes of CALLISTO has been made on the main principle to enable a low entry barrier for all team members, despite their technical or cultural background, using existing software and infrastructure only. Therefore, the identified improvements can broadly be classified as enhancements within or beyond these boundaries.

4.1 Possible process improvements within current technological and programmatic boundaries

As explained in Chapter 3, practical collaboration heavily relies on a virtual workspace based on Microsoft SharePoint named GALAXI. A switch from classical Windows like “folder” based organization of the workspace to a “metadata” based organization without folder was decided in 2020. The rationale for this change was that with the folder based organization, team members that were not working on CALLISTO on a daily basis had difficulties either finding existing documents (they did not know in which folder to look at) or deciding in which folder to place a documents. This problem was partly solved with the “metadata” organization. Metadatas are basically “tags” or properties that are given to a document. A custom-made set of mandatory and optional “tags” to be chosen within a predefined list was established (Document Type, Status, Product Breakdown Structure identifier, Issuer entity, Topic, Event) and all documents are now deposited at the “root” space. Finding documents now relies on using filters by metadata or a search tool. Users can either view the full list of documents at once, use one of the shortcuts to a filtered view or create and save their own filtered view. The feedback on the use of metadata is that there is a wide difference between trained and non-trained users: non-trained users tend to skip the optional tagging and add some properties, like “draft” status, directly in the name of the document. They also tend to have difficulty in finding documents. The recommendation would then be to have a specific training on metadata use for all newcomers.
The automated file versioning feature of GALAXI has strongly helped to reduce duplicates of documents, and therefore to maintain a better project-wide single source of truth. However, this feature has been mostly used during the collaborative editing phase of each document to enable the rollback of changes. For the approval of documents another manual versioning scheme has been introduced, indicating an edition number for each signed document and their approved revisions. Here, better integration of the approval workflow into the platform might be possible, so that the overhead for an additional manual versioning scheme would not be needed anymore.

Another recommendation that could be formulated is that special care should be given to monitoring “user experiences” in general on a regular basis. Indeed, some usability issues have been reported by external users, and a smooth integration with local software or online editing features could not yet be provided for all users. Situation of different user groups may also change over time as each entity IT means evolves and new problems could arise. The fact that there has not been, so far, a dedicated “process” set up for users to express their feedback or report problems on a regular basis, possibly prevented from efficient problem solving and improvements that would have make the collaborative work easier.
Given the importance of a smooth usage of the “collaborative virtual workspace” on a daily basis, a survey of user experience should be planned at least twice a year to detect anomalies and possible improvements (like addition of metadata, addition of specific user views, improvement of document search). Also, a direct interface between the IT provider and all user groups, e.g. via a unified ticket system, would be helpful to provide solutions in a timely manner.

On top of that, a systematic half-day training should be set-up, not only to introduce some key documents of the project, but also to explain what all team members should know about the collaborative virtual workspace and processes. Experience shows that although some “quick users guides” are available, they are scarcely used and known, and most new-comers “dive in” without training.

4.2 Possible process improvements beyond current boundaries

As explained in chapter 3 the main design principle was to optimize the usability and acceptance for a large heterogeneous user base, by relying mostly on a document-oriented workflow within the Microsoft Office ecosystem. So far, good machine readability of the exchanged information has not been a design driver, which could therefore be

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improved to leverage recent progresses in the fields of model-based systems engineering, data science, artificial intelligence and advanced AIV (Assembly, Integration and Validation) into the collaborative workflow. Here, the largest potential for improvement would be a possibility to exchange linked and semantic data. However, a very flexible and adaptable knowledge-management framework would be needed to ensure high usability for machines as well as for humans, which seems currently beyond state of the art.

It has been observed that effective software interfaces are necessary to enable a digitalized workflow across all teams. While the GALAXI platform provides common web and REST (Representational State Transfer) interfaces, these have been designed and optimized for the Microsoft Office ecosystem, so that the integration in other existing toolchains has been difficult. These toolchains have been built for example around Atlassian Confluence, version control systems like Git or Subversion, commercial CAD (Computer-Aided Design) software or scientific software like Matlab/Simulink. The application of free and open software standards would have likely helped for a more seamless integration, leveraging the existing heritage into the collaborative workflow.

Generally, it can be seen that a digitalized collaborative development process requires high documentation effort, which generates some management and maintenance overhead for the involved persons. As a possible mitigation strategy it has been identified that the reduction of the information chunk size , from monolithic documents to more atomic information bits, would support the reusability of content in multiple contexts. Also, automated build and deployment pipelines may help to simplify recurring tasks, and hence to allocate more workforce to the actual development activities.

Another observed characteristic of multilateral development processes for space systems are various different export control and cyber security policies that need to be followed by the involved entities. Therefore, it might be suitable to use a distributed database with a common cloud interface instead of one centralized server. This way, each data owner can keep legal control about their intellectual property on their own servers, while still allowing a collaborative workflow though the joint interface. Such cloud platform solutions are currently under development [12].

4.3 Lesson’s learned on working on different time zones with different culture

Face-to-face meetings are not just “nice to have” when working in different time zones on a daily basis: CALLISTO’s in-person workshops have always been the source of major progress in the project, as well as in the mutual understanding and team spirit in general. Taking your phone for a quick call for a clarification or an informal discussion can be natural on a same time zone and with people you know, but it is not practical between Europe and Japan due to time zones constraints. Creating a space were informal exchange is possible on top of official meetings is difficult in this context and in-person workshop provide this opportunity on top of the direct benefit of having more than 2 hours to work together on a topic.
Also, even within a given time zone, meeting in person on a regular basis allows knowing and “on-boarding” new team members and to build a relationship allowing the subsequent “quick call” option. In addition, face-to-face meeting is the only real effective way to create a team spirit in such a diverse team.
Another lesson learned is to never assume the other party understands what is “implied although not explicitly mentioned”. In CALLISTO we have observed different experiences and habits: what seems obvious to one may not be for the other due to different background or culture. Being explicit, reformulating and making sure of the understanding of the other party is never a loss of time. A simple illustration of necessary “explicitation” has been presented in Figure 5: conventions that may seem as common as “pitch” and “yaw” can actually differ within European borders.

5. Conclusion

All space vehicle developments are known to be highly complex. CALLISTO is no exception and faces the extra challenge of cooperation across 3 continents & time zones involving a variety of cultures. Practical solutions that have been set-up for efficient collaborative work rely on a web-based workspace (based on Microsoft SharePoint technology) hosting mostly Word and Excel files organized by metadata, with specific virtual spaces, templates and management processes for Interface Control Documents, System Engineering Data Base, Configuration Control and

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requirements. Generally, these implemented solutions have proven their effectiveness under "real-life" project conditions within CALLISTO.

Nevertheless, some lessons learned are drawn on tools and processes, like the importance on securing some time for training newcomers on the collaborative workspace architectures and the way they are used. Having dedicated milestones or surveys on the tools and processes on a regular basis allows to detect issue and implement improvements. Also, some recommendations for further development of collaborative tools, beyond the current state-of-the-art, have been derived.

Regardless of the tools and processes, CALLISTO's experience shows that to overcome the hurdles of time zones and cultural differences, it is necessary to dedicate time for face-to-face workshops and, in general, take time to avoid any implicit language in the technical exchanges.

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