ICI LLD - A ROCKY ROAD TO A SUCCESSFUL DEVELOPMENT

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ABSTRACT

At first glance, the Ice Cloud Imager (ICI) Launch Lock Device (LLD) does not look very different from many other HDRMs. However, the development of this mechanism was not without its challenges, eventually leading to a failed PDR and a complete change of the baseline design with consequences at instrument level. This paper discusses the processes, choices and behaviours that led to this situation and the recovery actions undertaken to rectify it. The lessons (re-)learnt in this project can be divided in a number of topics:

- Requirement specification
- Non-linear features in mechanisms
- Evolution towards design complexity
- Dilution of responsibilities
- Financial considerations

INTRODUCTION

Virtually all developments of spacecraft equipment at one point or another run into challenges or setbacks. The development of the Ice Cloud Imager (ICI) Launch Lock Device (LLD) is no exception. However, this hold down and release mechanism (HDRM), while at first glance not very different from other HDRMs, did not pass the PDR and required a complete baseline design change as well as instrument level design changes. The many iterations of the design are a testament to the difficulty of the process (Figure 3).

As the development of the LLD is nearing its end, with the flight hardware build and verification campaign in a very advanced stage, it seems an appropriate time to look back at what could have been done better. With the benefit of hindsight, it is possible to learn some lessons from this development. Interestingly, while some lessons learnt are purely technical, others are linked to more human traits, such as behaviour in a crisis situation or breakdown of trust.

A paper like this one can only be successful if the lessons are learnt in an open, constructive atmosphere. Therefore, all four partners involved, mechanism supplier, instrument prime, spacecraft prime and ESA, are co-authoring this paper. The content originates from the authors memories, as well as from documentation of the (many) meetings held at the time events unfolded.

THE ICE CLOUD IMAGER INSTRUMENT

The ICI as shown in Figure 1 is a conical scanning sub-mm wave imaging radiometer for MetOp-SG, developed by Airbus DS Spain for ESA/EUMETSAT. Its main objective is measuring ice cloud properties to improve numerical weather prediction and climate models [1].

Figure 1: ICI Structural Test Model (STM)

The ICI instrument consists of a fixed platform (FP) and an instrument rotating platform (IRP), connected by the Scan Mechanism Assembly (SCMA) in orbit and the LLDs in launch configuration. The SCMA is the mechanism allowing the rotation of the instrument [2]. The ICI instrument needs a set of three LLDs to hold the rotating platform, withstand all the environmental loads, release when externally commanded to do so and allow for a vertical displacement of several millimetres (Figure 2) and indefinite rotation of the IRP without subsequent interference of the LLDs. The vertical displacement of the IRP is not provided by the LLD but by the SCMA.

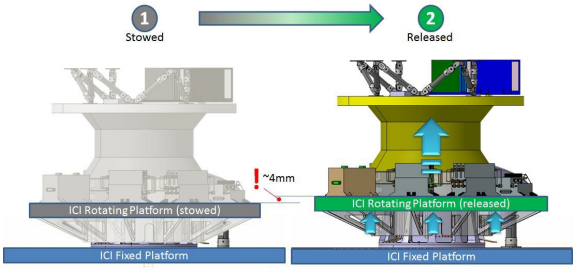

Figure 2: ICI deployment sequence (LLDs not shown).

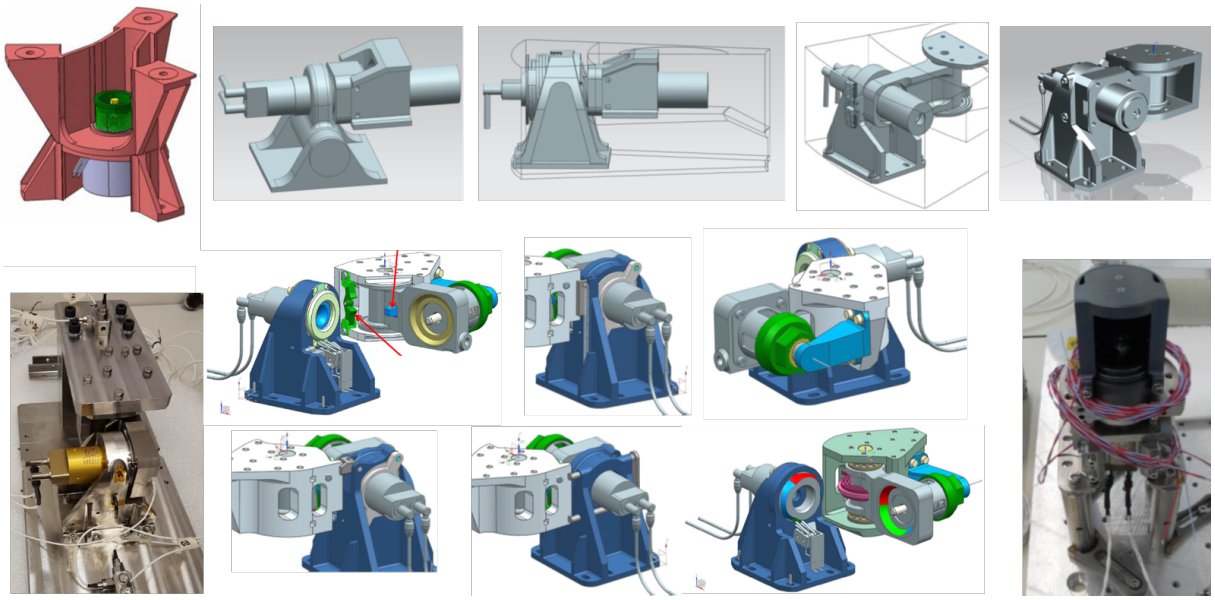

Figure 3: The many iterations of the ICI LLD

REQUIREMENT SPECIFICATION

How a problem is constrained can influence the solution hugely. The responsibility of defining a good set of requirements does not only lie with the writer of the requirement specification (RS), in this case the instrument prime. The spacecraft prime is the owner of top-level requirements, which can inadvertently lead to problems at lower levels. ESA has visibility of the entire specification flow down and should ensure consistency, feasibility and even necessity of certain requirements. However, the mechanism supplier also has the responsibility to challenge requirements, and highlight opportunity for simplification. In this process, it is important not to exclude any requirements if the potential benefits of a relaxation are sufficiently large.

From the procurement process, over the requirements review (RR) to the PDR, there were several indications that some requirements were responsible for the complexity of the proposed mechanism concept. In this paragraph, the driving requirements will be discussed. The goal is to expose how they influenced the design, evolved throughout the design process, and which potential opportunities for simplification may have been missed.

There are 6 issues of the RS. Issue 2 is applicable at invitation to tender (ITT). Issue 3 and 4 are a result of changes related to the original design. Issue 5 and 6 are used after the change of the concept.

LLD Early Design Concept

Prior to scrutinising the driving requirements, their influence on the design and their evolution, it is important to introduce the original LLD design concept. Interestingly, the design itself influenced the RS and the verification approach to a significant extent.

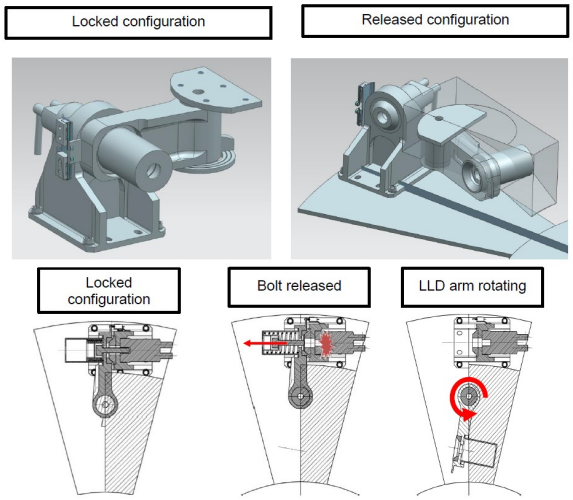

Figure 4: LLD design concept and deployment sequence

The original LLD design concept consists of two parts (Figure 4).

- The bolt retainer and a conical I/F facing the fixed part of the instrument are placed on the IRP. These components are part of a rotating arm that has its hinge axis parallel to the instrument rotation axis.
- On the FP, a spherical I/F is facing the conical target on the rotating I/F; this sphere is part of a fixed structure.

The bolt preload is needed to avoid separation of the sphere and cone during launch. Once the separation signal is received, the bolt is retracted in the bolt retainer, the preload is removed and the LLD movable part on the IRP can rotate around the vertical axis separating the contact surfaces.

The hinge in the LLD is immediately obvious, but the sphere-cone interface allows for rotation under certain conditions and therefore essentially introduces a second hinge. As a result, the LLDs can only withstand the loads and provide the required stiffness when working together. The verification of the environmental loads and stiffness therefore needs to be performed as a system. Whereas it is possible to verify stiffness and strength of a single LLD, by constraining the DOFs normally constrained by the other LLDs, the most logical verification makes use of an IRP mass dummy.

Envelope

Figure 5 shows the envelope requirement in the earlier issues of the RS. The height of the envelope is driven by the distance between the FP and IRP for the instrument in locked configuration. The cyan part of the volume is allocated to the part of the LLD remaining with the FP, whereas the green part is allocated to the part of the LLD remaining with the IRP upon separation. The split in the volume is a consequence of structure on the underside of the IRP, and avoids clashes during rotation.

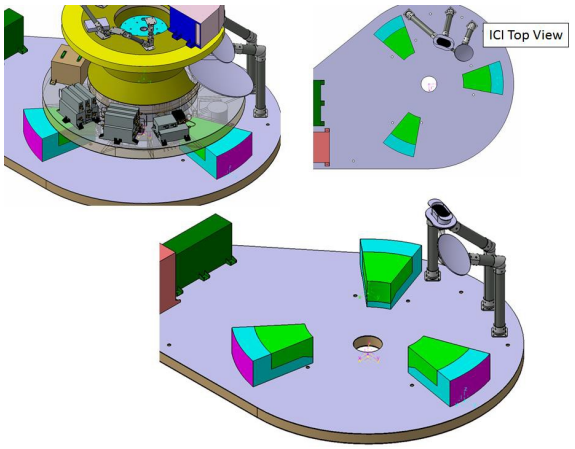

Figure 5: Envelope requirement in RS issue 2, 3 and 4.

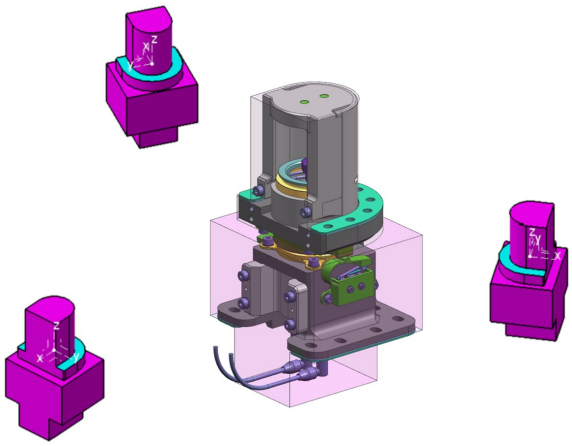

Figure 6: Envelope requirement in RS issue 5 and 6. LLD design concept after design change compared to the new envelope requirement (centre).

Using the loads requirement, the mechanisms supplier sized the release actuator for a certain preload range. The size of the actuator in conjunction with the provided envelope lead to the actuator being oriented in-plane. This immediately results in a more complicated concept. There could have been a possibility to highlight the benefits of a larger out of plane volume earlier in the project in a proactive fashion. However, the mechanism supplier considered the envelope requirement as a fixed requirement, in contrast to other requirements such as loads, stiffness and mass, where a relaxation of the requirement is more common.

The tight envelope requirement could have been identified in the frame of the ITT data pack preparation, by the spacecraft prime or ESA in their review capacity. Further investigation could have revealed the difficulty to fit a suitable actuator in the most logical orientation.

Figure 6 shows the updated envelope requirement. The requirement was relaxed significantly, allowing for excursions into the volume of the IRP and the FP. The requirement was only relaxed after the failed PDR, when the mechanisms supplier proposed a simpler LLD concept. Comparing the new envelope to the design (Figure 6) clearly shows the requirement was tailored to the proposed solution. Unfortunately, at that point in time the instrument design had matured and a significant, costly redesign of the instrument was required in order to accommodate for the updated envelope.

As a side note, accessibility has been a concern throughout the development. The actuator needs to be reset after every actuation and therefore needs to be removed from the LLD. In the original design concept, the actuator was more easily reachable as it was not positioned underneath the IRP. However, the final design proved that it is feasible to perform all refurbishment activities in a more difficult to reach location. A dedicated requirement was added to define the volume available to the operator to preload the LLD and perform refurbishment activities.

Clearance

Figure 7 shows the evolution of the clearance requirement, controlling the minimum distance between the part of the LLD attached to the IRP and the part attached to the FP. The SCMA only provides a limited vertical stroke to the instrument. Therefore, this requirement was scrutinised prior to the ITT and the instrument prime provided a detailed analysis to account for all factors potentially reducing the original gap after release, such as thermo-elastic distortions, instrument unbalance or IRP/FP flatness.

The requirement as written in issue 2 does not allow for any overlap of the LLD parts, such as a cup-cone or sphere-cone interface. The requirement as written would therefore not have been met by the final LLD design.

In issue 3 and 4, the requirement was already relaxed, providing a 4mm vertical stroke. Issue 2 of the requirement still accounted for an alternative SCMA supplier, which had a design with a smaller stroke.
Issue 5 and 6 required a further update, as the gap does not only need to be controlled between the different parts of one LLD, but also with respect to the released parts of the other LLDs. The hinged LLD concept did not need this requirement refinement, but it was an essential update after the design change.
The clearance requirement was never a driver for the design concept, since there was not sufficient volume to place an appropriate actuator in the vertical direction. In case the envelope would have been larger, the original requirement could have influenced the design, allowing only for a flat on flat design for the separation surfaces.

ICI-LLD-116 / / T,A,R

Once released, the minimum distance between the part attached to the rotating platform and the one attached to the fixed one shall be maximised and never lower than 2.5 [mm] in any direction after a vertical displacement of the ICI rotating platform of 3 ± 0.5 [mm].

ICI-LLD-116 / / T,A,R

Once released, the minimum distance between the part attached to the rotating platform and the one attached to the fixed one shall be maximised and never lower than 2.5 [mm] in any direction after a vertical displacement of the ICI rotating platform of 4 ± 0.1 [mm].

ICI-LLD-116 / / T,A,R

With the definition of ROTATING_PLANE and FIXED_PLANE provided in [AD-349], once released, the minimum distance between:

- *LLD fixed part and ROTATING_PLANE (case A)*
- *LLD fixed part and LLD rotating part (case B)*
- *LLD rotating part and FIXED_PLANE (case C)*

shall be maximised and never lower than 2.5 [mm] in any direction after a vertical displacement of the ICI rotating platform of 4 ± 0.1 [mm] ($+Z_{SRT}$) across the full instrument rotation taking into account:

- *The ROTATING_PLANE is defined with respect to the IRP I/F so it has to be considered translated vertically also 4 ± 0.1 [mm] with this part of the instrument.*
- *Ideal instrument interfaces:*
  - *Perfect paralelism between IRPs and BPs*
  - *Coplanar IRPs*
  - *Coplanar BPs*

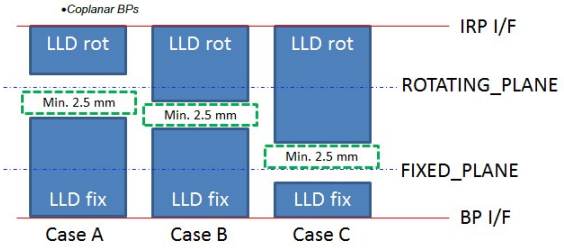

Figure 7: Clearance requirement in RS. Top: Issue 2. Middle: Issue 3 and 4. Bottom: Issue 5 and 6.

Loads

Figure 8 shows the loads requirement evolution. The loads requirement was challenged by the mechanisms supplier from the start of the project, proactively proposing an alternative approach. Specifically, the high interface moment loads were deemed to be challenging.
The loads requirement had not yet matured at the RR. This could and perhaps should have lead to a failed RR, although this would not have sped up the process of converging on a mature requirement. The derivation of the load case was also a point of discussion between the instrument prime and spacecraft prime. The loads requirement eventually stabilised in issue 3 of the RS, but was defined as a quasi-static load with an IRP mass dummy.

ICI-LLD-98 / / T,A

Each LLD shall withstand the combination of the following loads (Limit Loads):

- *$F_{in\text{-}plane}$ = 7430 [N]*
- *F_z = 8903 [N]*
- *M_r = 265 [Nm]*
- *M_θ =157 [Nm]*
- *M_Z = 13 [Nm]*

These loads are to be considered as the envelope resulting of the CLA within the ICI instrument. If LLD design is such that some of its rotational stiffness values are to be considered zero, final limit loads shall be agreed with the instrument prime.

Clarification: qualification loads are to be derived (as stated in ECSS-ST-33-01C Mechanisms) by applying a KQ of 1.25 to the Limit Loads).

ICI-LLD-150 / / T,A

ICI LLDs in preloaded configuration with an instrument representative dummy mass on top as defined in ICI-LLD-109 shall be compatible to the quasi-static loads defined in Table 4.5-1 (reference axes defined in ICI-LLD-106).

QSL (design limit loads)	//	//	⊥
ICI	X	Y	Z
Combined loading	+/-25.95g		+/-17.30g

Table 4.5-1: ICI LLDs QSL

ICI-LLD-150 / INS-GDI-1757,Derived,ICI-396,Derived / T,A

Each LLD shall withstand the combination of the following loads (Design Limit Loads):

- *Max inplane IRP IF reversible force $F_{inplane}$ = 8500N*
- *Max outofplane IRP IF reversible force $F_{outofplane}$ =9500N*
- *Max IRP IF deflection under dynamic environment $\delta_{inplane} \leq 0.26$ deg (in plane direction). Displacement to be understood applied at IRP I/F plane intersection with Z_{LLD}.*

Figure 8: Loads requirement in RS. Top: Issue 2. Middle: Issue 3 and 4. Bottom: Issue 5 and 6.

Part of the difficulty in defining the loads requirement results from the nature of the LLD design, as the load distribution depends on its specific. Interface loads depend on the LLD design, and could therefore not be specified, leading to the definition of the requirement as a QSL. Uncertainty of the load distribution also complicated the dimensioning of the instrument structure, which sees the same loads.
After the change of the concept design, the load requirement reverted back to a definition of loads at LLD level. It has to be noted that the moment requirement has been replaced by a maximum angular deflection of the IRP. This takes into account that a relative motion takes place between the sphere and cone, so in certain conditions the moment load capability is zero. Only for low loads, some moment load capability is present based on the friction in the sphere-cone interface.

Stiffness

Figure 9 shows the stiffness requirement evolution. The difficulty to meet this requirement is the immediate trigger which lead to the failed PDR and consequent change of the baseline design. The stiffness behaviour is also directly linked to the non-linear mechanisms features discussed in detail later. In addition, due to this non-linear behaviour, there is a link with the changes in the load requirement. As the loads increased, it became harder to meet the stiffness requirement.
During contract negotiation, the stiffness requirement changes from a static requirement to a requirement in frequency, considering the system with an IRP dummy. With the margins applied, a first frequency of 171Hz is specified. However, as the program evolves, the mechanisms supplier states they can no longer be compliant to the stiffness requirement.

ICI-LLD-99 / / T,A

Each LLD shall have a static stiffness greater or equal to:

- $K_{radial} \geq 7e7$ [N/m]
- $K_{tang} \geq 7e6$ [N/m]
- $K_Z \geq 7e7$ [N/m]
- Ktt, Krr, Kzz > 5e5 [Nm/rad] (TBC)

Any deviation from this values shall be agreed with the customer.

ICI-LLD-153 / / A

The first fundamental frequency (non rotational) of the ICI LLDs in preloaded configuration with a rigid body with the properties defined in ICI-LLD-109 shall be greater than 148.7Hz. Pure rotational lower first mode may be accepted by the Prime.

Note: According to GDI-277, a margin of 15% shall be applied to these analyses.

ICI-LLD-153 / INS-GDI-1745,Derived / T,A

Each LLD shall provide the following static stiffness values according to the LLD local reference axes defined in ICI-LLD-44 between its two interfaces:

Kradial ≥ 7e7 N/m

Ktangential ≥ 7e6 N/m

Kz ≥ 7e7 N/m

Krradial ≥ 0 Nm/rad

Krtangential ≥ 0 Nm/rad

Krz ≥ 0 Nm/rad

Note: baseplate I/F clamped, IRP I/F blocked rotations.

Figure 9: Stiffness requirement in RS. Top: Issue 2. Middle: Issue 4. Bottom: Issue 5 and 6.

In the following iterations of the design, the achievable first frequency is 151Hz (even though the requirement remains 171Hz). The acceptibility of this lower performance is assessed at instrument level, in the frame of a request for deviation (RFD) assessment. In order to do so, a degraded model, based on a more complicated non-linear model, is delivered to the instrument prime. The performance is in principle considered acceptable, even though the RFD is not yet formally approved.

During the detailed design phase, an updated FEM is delivered, where the rotations at the separable surfaces are released. This was not the case in the earlier delivered model, but is a more realistic representation of the actual behaviour of the mechanisms, as sliding in the sphere-cone interface is confirmed in the mean time. At mechanism level, this has no impact on the first frequency, as an assessment is made with a rigid IRP dummy. However, when the updated LLD model is included in the instrument model, an unacceptable reduction of the stiffness is uncovered. The stiffness requirement created boundary conditions that are not realistic of the instrument (due to the rigid IRP dummy). This resulted in a situation where a mechanism design was possible with a certain performance, an overall stiffness of 151Hz, which resulted in insufficient stiffness at instrument level. The significance of the boundary conditions was not fully appreciated. It needs to be highlighted that if the LLD would have met the actual requirement of 171Hz, there would not have been a problem at instrument level, regardless of the change in boundary condition.

After this finding, a significant amount of effort is spent on updates to the LLD design which intended to reduce or remove the impact of non-linear features in the hinge and separable surfaces and recover the stiffness performance. Eventually, the change in baseline design allows for a change to the original requirements (Figure 9), with the exception of the rotation stiffness which cannot be guaranteed in the sphere-cone interface.

NON-LINEAR MECHANISM FEATURES

Non-linear features in spacecraft mechanism design can lead to difficulties in terms of performance and performance verification. Verification by analysis requires elaborate non-linear analyses. Test campaigns can also be hampered by non-linear behaviour.

Non-linear features typically require dedicated testing during the development. In a problem situation, it may be advisable to design out these features if possible. Non-linear features are perceived as risks, because the design can be inherently complicated or because performance predicted by analysis can deviate from hardware behaviour. Furthermore, it can be difficult to guarantee identical unit-to-unit behaviour.

The PDR version of the LLD design included gapping in a hinge and intentional slippage in the separable surfaces. Several features were proposed, in the PDR design as well as afterwards, to mitigate these effects.

Sliding

Sliding in the separable surfaces was known in the very early stages of the design. The LLDs are not released synchronously. Therefore, the last LLD to be released is exposed to a moment load, generated by the force in the SCMA used for the vertical deployment of the IRP. In order to mitigate this, an end stop was introduced in the design (Figure 10).

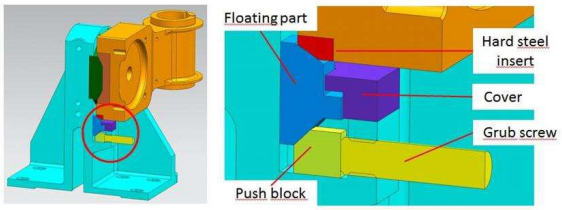

Figure 10: End stop to avoid sliding because of asynchronous LLD release

As the design matured, the friction values between sphere and cone were measured in breadboard tests and found to be very low. Consequently, sliding occurs not only due to asynchronous release, but also during vibration. Sliding in the separable surfaces affects the stiffness of the LLD. Furthermore, it poses a risk of a non-successful separation.

Two design solutions have been proposed (Figure 11). A tri-pod solution, using three intersecting sphere-cone interfaces, would be able to take a moment load. This would avoid sliding altogether and remove the non-linear behaviour, and therefore yield a better stiffness performance. A second concept proposed included an intermediate ring, which still slides, but avoids relative motion between the separable surfaces.

The final design of the LLD actually still includes sliding between the sphere and cone. However, an extensive breadboard test campaign retired the risks.

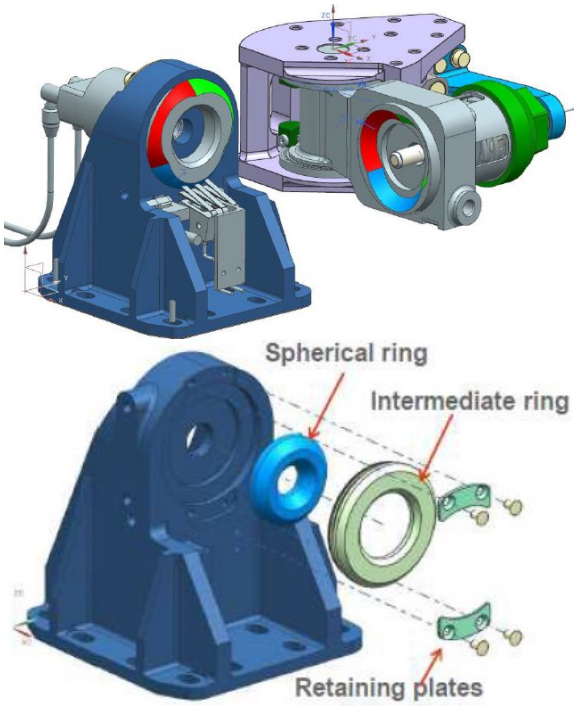

Figure 11: Design features to mitigate sliding. Top: Tri-pod solution. Bottom: Intermediate spherical ring.

Gapping

The LLD hinge uses a simple plain bearing. As a result, the hinge free play is not zero. This creates non-linear behaviour and has an impact on the stiffness behaviour. At PDR, a first potential solution for this behaviour was proposed by the mechanisms supplier (Figure 12), employing a concept to block the lever arm. A second concept further refined this idea. The third concept utilised a thrust bearing solution. None of these concepts matured to satisfaction of all partners.

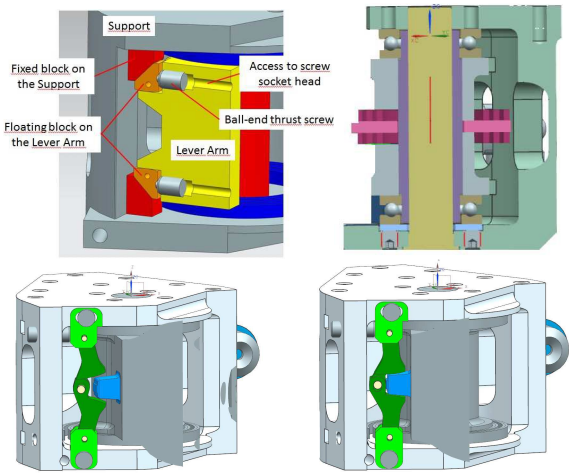

Figure 12: Design features to mitigate gapping. Top left: Lever arm blocked concept. Top right: Thrust bearing concept. Bottom: Rod end-stop concept.

WAY FORWARD AFTER FAILED PDR

Once it became apparent the PDR would not successfully be concluded, all parties involved cooperated intensively to come to a solution. There are several observations that can be made:

- The design evolved to become progressively more complex.
- The design responsibilities became less clear.
- The initial focus was on the design, whereas a serious investigation of the requirements was only performed at a later stage.

Evolution towards complexity

The previous chapter, showing some of the design concepts investigated to mitigate the non-linear features, illustrates the design solutions became progressively more complicated. Only a sub-set of the many proposed design solutions have been shown in this paper.

It is a testament to the creativity of the engineers involved that many potential solutions were found. Unfortunately, more complicated designs have a lower chance of success in such a situation. It is important to highlight that in the case of the ICI LLD there were no clear technical showstoppers for several designs proposed. However, the most promising solutions required some testing activities to prove their feasibility, which was incompatible with programmatic constraints as schedule constraints and cost overruns impact decisions.

Less obvious, but likely equally important, is the fact that working relationships in a crisis can become strained. A complex design provides ground for many discussions and does not instil trust. With a simpler design concept, such as the one eventually proposed, it is immediately obvious to all parties involved that a functional solution will be reached.

Dilution of responsibilities

On a related note, the different parties of the customer chain are inclined to proactively propose alternative design ideas and concepts. The downside is that the relative responsibilities are diluted and the contractor efforts spread in different directions.

It is difficult for a supplier in such a situation to refuse to assess an alternative design proposed by the customer chain. In this case, it lead to a design concept taking up a lot of resources, even if the mechanisms supplier highlighted not being comfortable with the concept as they had no previous heritage or design experience related to the specific concept.

There is nothing inherently wrong with providing ideas, but the design responsibility should remain clearly in the hands of the mechanism supplier. The customer chain can instead focus on ways to simplify the problem, for example by reviewing and where possible relaxing the requirements.

Fix the problem, not the design

The first months after the PDR focussed predominantly on trying to improve the design. It took a long time before significant attention was given to the requirements. Eventually, the instrument supplier instigated a review of the requirements with the spacecraft prime and ESA and asked the mechanisms supplier to provide a critical assessment of the driving requirements.
The instrument supplier subsequently confirmed the validity of the vast majority of the requirements. The mechanism supplier from their side confirmed a difficulty to reach a credible design with the set of requirements as they were. During this exercise, they proposed a much simpler design, which required the envelope requirement to be relaxed. This eventually proved the correct way forward.
Relaxing the envelope requirement required several costly updates at instrument level. It may not have been possible to achieve this particular solution if the situation had not yet been this critical. However, it is likely that instigating a critical assessment of the requirements earlier would have tabled the simpler design option sooner.

FINANCIAL CONSIDERATIONS

The changes at instrument level to accommodate the new LLD design include:
- Instrument structure redesign
- Instrument architecture design by changing equipment accommodation on the IRP
- MGSE redesign
- Updates to the SCMA
- Harness redesign

The updated LLD design requires a significant effort by the mechanism supplier:
- Repeating PDR for a new design
- A dedicated breadboard campaign to retire risks related to potential fretting in the separable surfaces

However, significant cost savings are achieved by reverting to a simpler mechanical design and a simpler verification campaign.
It is clear that the effort required at instrument level and by the mechanisms supplier come at a significant additional cost. In a commercial environment, obtaining a financial arrangement satisfactory to all partners can be difficult. In such a situation, it is clear there cannot be ‘winners’. At some point, it may be possible to unblock a difficult situation by an injection of additional funding, by the spacecraft prime and/or ESA, but only once a credible technical solution is found.

THE ICI LLD – A SUCCESS STORY

Once the technical and programmatic way forward had been agreed, it took only 3.5 months to reach delta-PDR. CDR was completed 8 months after that and the QR closed out 3 months later. The set of LLDs to be used at instrument STM, which at one point were on the critical path, were delivered on time. At the time of writing, FM1 and FM2 flight sets have completed their acceptance test campaign and are waiting the formal review of test results before delivery. The FM3 flight set is starting its acceptance test campaign.
The LLD is composed of 2 subassemblies (Figure 13):
- The base assembly, which remains fixed to FP after the LLD release; it provides the lower separation interface and hosts the release device.
- The upper assembly, which remains on the IRP after LLD release. It is composed the upper separation interface and the bolt catcher.

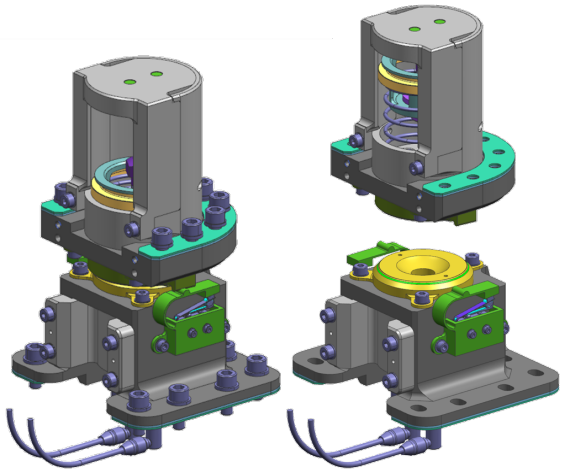

Figure 13: The final ICI LLD design. Left: Locked. Right: Deployed.

The most challenging part of the development of the final LLD concept was related to the separation surfaces. The geometry, material and lubrication is identical to the original LLD design. This enabled to build on the lessons learnt in the previous breadboard test campaign. However, also in this version of the LLD, relative rotation was possible between the sphere and cone. From an instrument point of view, this behaviour was deemed acceptable. The risk to be retired was related to the successful functioning of the sphere-cone during separation.
A dedicated test campaign was performed in order to demonstrate the ability of the LLD separation surfaces to withstand the loads experienced during the life. However, the verification approach had been reverted from a system level approach to verification at LLD level. It was therefore difficult to represent the loading seen during vibration test. Via analysis, an estimate was made of the number of cycles and the related amplitude which would be seen at the separation surfaces.

The test campaign consisted of the following steps:

- Adhesion force was measured in vacuum.
- Enforced rotation around X and Y with different amplitude and different frequency superimposing a constant vertical load (representing the minimum and maximum contact pressure) half of the cycle in tension and half in compression. This step was performed in ambient.
- Adhesion force after enforced rotation was measured in vacuum.
- 74 cycles of preloading performed in ambient.
- Adhesion force after the cycles, measured in vacuum.

The lubricant leaves a dark sign on the surfaces (Figure 14). Inspections between load cycles and after the adhesion test resulted in no visible deviation from what was observed in the inspections after the fretting test phase. No lubricant migration from the contact line was observed, thus no direct metal-to-metal contact occurred. The measured adhesion force after the fretting test was very low, confirming the design is fit for purpose.

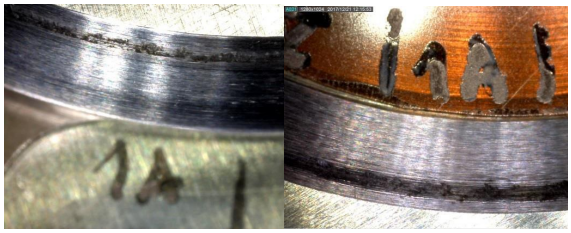

Figure 14: Post-fretting test inspection. Left: Sphere, after cleaning. Right: Cone, after cleaning.

The main parameter where the final LLD design differs from the hinged LLD design is stiffness performance. Table 1 shows the stiffness requirement compared to the predicted stiffness for both LLD designs in an early stage of development. It is clear the hinged LLD stiffness performance was marginal to begin with, and proved challenging to achieve as the design matured. The final LLD had a much more comfortable margin with respect to the stiffness requirement. In addition, the achieved stiffness performance as verified by test was very close to the predicted values. The final LLD design, made possible by updating the requirements, is therefore more robust from a stiffness point of view.

Table 1: Stiffness requirement vs early stiffness predictions for both LLD concepts

	Requirement	Hinged LLD	Final LLD
K_{radial}	$7e^7$ N/m	$7.88e^7$ N/m	$1.67e^8$ N/m
$K_{tangential}$	$7e^6$ N/m	$6.80e^6$ N/m	$1.65e^8$ N/m
K_z	$7e^7$ N/m	$6.81e^7$ N/m	$2.69e^8$ N/m

CONCLUSIONS

There is not one clearly identifiable technical reason why the hinged concept did not successfully mature. Rather, a combination of technical reasons contributed to a lack of belief in the concept. In fact, it may well have been technically possible to develop a hinged LLD meeting the requirements of ICI. However, numerous non-technical reasons, such as schedule pressure, financial considerations, and a lack of trust in the robustness of the design concept, are what lead to a change of the baseline concept and verification approach.

There are several lessons that can be learnt, or re-learnt, from this development:

- A properly bounded problem will lead to a better concept design.
- It is possible to challenge any requirement at any time.
- At project kick off, or at RR, an explicit effort can be made to look for potential for simplification if any of the requirements can be relaxed. This can be added as a RR objective.
- If a design is marginal on stiffness, the boundary conditions should be carefully considered as they can influence the overall stiffness performance.
- Engineers will often try to fix the problem at hand, leading to an increase in complexity. In some cases, the problem can be solved by simplifying instead.
- The design responsibility should clearly remain with the contractor responsible for the design
- Financial considerations can influence the process of solving the problem. Relieving them can be very useful.

When a design process runs into trouble, it is important to remain constructive, as happened in this case. It is usually possible to find a good technical solution and restore trust. In this case, a robust design of the ICI LLD has been achieved, as well as a very good working relationship between all parties involved.

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REFERENCES

1. Bergada, M. et al (2016). *The Ice Cloud Imager (ICI) Preliminary Design and Performance*. 14th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment (MicroRad).
2. I. Köker, C. Hehr, G. Parzianello (2017), *Design and Test of a Scan Mechanism for Microwave Imaging Instruments*. In Proc. 17th ESMATS 2017, Univ. of Hertfordshire, Hatfield, UK.