SPACE MECHANISM DEVELOPMENT LESSONS TO BE LEARNED – AN INDEPENDENT VIEW

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Abstract

Recent mergers within the European space industry are being followed by a period of post-merger rationalisation. A continuing challenge for both merged and independent organisations is to optimise hardware development and manufacture processes to minimise costs and commercial risks. In many cases organisations are taking the view that it may be more appropriate to sub-contract key aspects of mechanisms design, development and test either to centres of expertise within the organisation or to external specialists with whom they have close working relationships or partnerships.

One benefit of the latter approach is that the sub-contractor/consultant holds knowledge of common problem areas for mechanism developers and is therefore well placed to advise new clients to avoid recurrences.

This paper draws from the recent experience of two partner organisations involved in the design, development and test of spacecraft mechanisms on a consultancy and sub-contract basis to present a number of lessons learned which should be of wide applicability to future mechanisms developers.

1. Introduction

This paper discusses and exemplifies lessons learned in terms of different pre-flight stages of a typical generic mechanism programme, namely:

- Requirements Specification
- Design
- Procurement
- Development
- Build
- Test

The paper draws on experiences gained on a number of programmes, and some of the lessons may be considered to be obvious, avoidable, intuitive or organisation specific. However no organisation is immune from changes of structure or personnel and the frequency with which similar issues arise across industry and sometimes within the same company suggests that the lessons are nevertheless valuable despite attempts by individual organisations to capture and distil valuable lessons learned internally.

For each of the areas of the generic programme listed above our preference has been to relate issues discussed to identified programmes. However, this has not proved possible in all cases, and so we have also included un-attributed examples and those based on our general experiences in the field if the issues discussed are more frequently occurring in nature.

The aim is that by discussion we will raise awareness of the issues in such a way that the information may be directly applicable in future programmes.

2. Requirements Specification

A spacecraft has many subsystems and often has many mechanisms, yet traditionally there is no “mechanisms” subsystem. Mechanisms are an enabling technology only required on spacecraft to allow other subsystems or payloads to function. Therefore mechanisms are expected to meet the flowed-down subsystem requirements and constraints yet they must also meet the imposed requirements and standards for all space mechanisms (e.g. ECSS-E30-03).

Inevitably this situation creates conflicts and so rationalisation and compromise are an important part of the design development process so that the mechanism designer can deliver the right product at the right price and the right time.

To enable rationalisation and compromise, the mechanism design team must participate to some extent in the system design to establish a clear specification and then be permitted to take a system approach to flowing-down those requirements to lower tiers (e.g. bought-in components, materials, drive electronics, sensors etc.) in a logical manner.

Though the above may seem obvious, in practice it is not always the case that this logical approach to the requirements specification process occurs. Examples of where this approach has been effectively used are ESA development contracts, such as the Antenna Pointing Mechanism with Multiple RF Feedthrough, where the higher level RF requirements were given a high priority and the APM designed to service those requirements. A further example of good practice is the Skybridge APM programme where an integrated product team approach was taken to allow the APM specification to evolve with requirement impacts and system options fully explored.

Perhaps surprisingly some of the poorest examples are those company-funded product development programmes where possibly due to the lack of self-discipline and system appreciation, the work has been undertaken with no clear specification or customer view inputs. In these cases the resulting product has often proved to be technically compromised and the company funds wasted.

A second example of poor practice in this area is where mechanism drive and control electronics are predefined by an external agency without accounting for any of the mechanisms flowed-down requirements or constraints. In at least one case this has lead to serious technical programme and cost problems for both customer and supplier.

Lesson Learned: A pre-requisite of a robust and achievable mechanism requirements specification is the inclusion of the mechanism design function in the system design and the subsequent use of a systems approach to flowing-down lower level requirements.

3. Design

For mechanisms, assuming a robust concept, problems are frequently found in the details of design and implementation. Therefore we include in this section a selection of specific detailed design lessons.

3.1 Use of Ball Bearings

Angular misalignment of bearings is clearly a critical issue. Experience suggests that angular misalignment of as little as 0.3millirad (i.e. 15 micron across a 50mm diameter bearing) can lead to high cage wear especially for metallic cages frequently used for solid-lubricated bearings which have high rigidity compared to polymers.

Sources of ball bearing misalignment which have been encountered include:

- Build up of tolerance loops
- Stress relaxation in thin diaphragms used to provide compliant preloading
- Incorrect selection of bearing seat radii such that bearings do not seat squarely into their locations.

Lesson Learned: Designers should be aware of the misalignment sources above and make provision by design to verify bearing alignment once installed.

3.2 Contamination Issues

Clearly in addition to the usual sources of contamination such as oils and greases which may be inevitable, designers can minimise by good design other sources of contamination. Examples include:

- Motor magnet fragments (see motors)
- Anti-creep barrier films misapplied prior to packaging with subsequent transfer to wrong areas.
- Use of tapped through-holes close to or above bearings such that any thread root debris, thread lubricant or adhesive residues may be progressively forced out of the tapped holes to enter the bearings

Lesson Learned: Consider means to manage debris sources generated during assembly by for example designing in provision for creep barriers and avoiding locating holes above bearings where possible.

3.3 Bearing Preload Control

Many applications require use of lightly preloaded angular contact bearings. In such cases designers may still rely on the limited axial elasticity of the bearings themselves plus precision shimming (sometimes less than 10 micron thick shims) to achieve the desired preload.

Some issues relating to this include:

- If “peelable” shims are used for preload setting there is potential for loss of preload over time due to adhesive or material creep.
- There may be high uncertainty over the actual preload set.
- Large variations in preload during thermal vacuum testing due to mismatch of thermal expansion coefficients at soak temperatures and under thermal gradients.

Though the latter can be predicted using typical bearing analysis software including CABARET (Ref. 1) the thermal environment must be accurately known. Unfortunately most thermal analysis codes do not accurately model the rather poor thermal conductivity at the bearing seats and consequently thermal gradients may in practice prove much larger than expected.

At higher preloads, other preload-setting problems can occur. Though bearing stiffness can be accurately predicted using bearing analysis software the combined axial and radial compliances of the bearing seats and structure cannot. These effects depend on fits and form errors can lead to an over-estimate of the combined bearing/structural stiffness.

Lesson Learned: There are many reasons why the as-built and as-designed bearing effective preload, (therefore torque) and stiffness may not be realised. Multiple design iterations on preload are to be expected.

3.4 Motor Design

For many space applications the prime movers are frameless motors, which are housed or integrated within the mechanism. Though the motor technology is mature, problems are still experienced in their use.

For stepper motors, the main problems are the dynamic characteristics of the motor when driving high inertial loads due to low resonant frequencies and damping. Stepper motors also employ very small rotor/stator gaps (typically less than 0.1mm diametral), thus care is needed in the control of tolerances and bearing stiffness to avoid rotor/stator contact. It is recommended that equispaced inspection holes are incorporated into the motor end-plates to enable verification of the rotor/stator gaps after assembly.

Other recommended precautions for all motor housing types are:

- Protection of exposed magnet surfaces by conformal coating to avoid possible chipping of magnet edges during assembly.

- Positive locking of all elements of the motor drive train, including rotor/shaft and stator/static housing interfaces. There should be no reliance on torque transmission through friction interfaces at any stage of the transmission chain. There have been several examples in the past where drive friction has been lost under thermal vacuum conditions when thermal differentials have reduced the effective preload and therefore the friction at the interfaces, see Figure 1.
- Simply bonding motor elements together is also not preferred as this has led to problems with bearing and in some cases commutator contamination in the past.

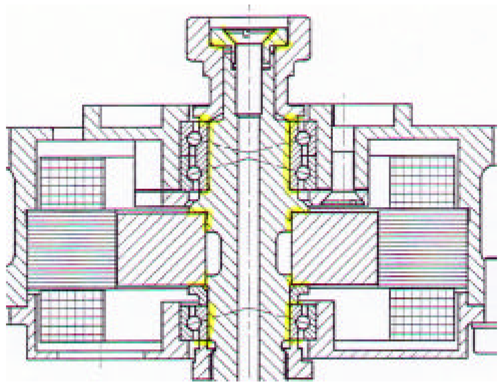

Figure 1 Example Of Motor Design Which Relies On Interface Friction

3.5 Flex-Pivot Design

Flexural pivots are widely used in the space industry as an alternative to ball bearings for applications which require motion through only a small angular range. The main advantages of flexpivots include long life without lubrication and very low friction/hysteresis losses. These characteristics are well suited to use in high-precision pointing/scanning systems. There have been a number of dramatic failures of these devices during vibration test. In addition to low friction and hysteresis about the torsional axis they exhibit similar properties in the translational axis and therefore the low damping within the pivots can lead to high response levels at the supported payload during vibration testing. In particular, for random vibration, the high "Q-factors" at resonance (>100) together with high mid-frequency PSD levels lead to very high pivot loads simultaneously applied along multiple axes.

To limit this problem, it has become quite common practice to use protection sleeves, which act as radial snubbers around the pivots.

By use of these sleeves the relative radial displacement of the rotating side of the flex-pivot is limited with respect to the static side and so the pivot radial stresses are constrained to acceptably low values. With such a configuration, radial gaps are typically set to take account of pivot strength, stiffness, centre shift, manufacturing and installation tolerance loops.

For such radial protection measures to be effective and to permit optimisation of the snubber gaps the pivot itself should have a high strength/stiffness ratio and well defined strength and stiffness data should be available.

In fact current pivot designs do not offer a particularly high strength/stiffness ratio, mainly due to their high radial stiffness. For some pivots, supplier stiffness data significantly underestimates the true stiffness, in some cases by more than 200%. Given this, it is extremely difficult to design and effective pivot protection system.

Similar problems are also encountered in the design of axial pivot protection sleeves due to the very high axial stiffness of the pivots, which can be as stiff as the surrounding support structure. In some cases therefore it has been necessary to introduce additional elastic elements into the structure to compensate for the high axial stiffness of the pivot.

Lesson Learned: Clearly existing designs of flex-pivots should be used for space only with extreme care and when supported by rigorous analysis, including detailed FEM and stress analysis of the pivots themselves and early vibration testing.

3.6 Dis-Assembly

To date ESTL has built around 200 flight or flight-standard mechanical assemblies, mainly to designs developed outside our organisation (with or without our support).

A significant number of these have had to be dis-assembled at some stage, usually due to late design changes as a result of parallel or near parallel development testing and build schedules or use of the protoflight approach.

In our experience – robust designs are those which permit easy assembly AND dis-assembly. Designers always think about the former, but in practice the latter is equally important to the project manager, for if an assembly cannot be taken apart there is often no option but to scrap it with consequential lead time and cost implications!

Lesson Learned:
Unless totally impractical design mechanisms to permit dis-assembly as well as assembly.

4. Procurement

In this section we discuss some procurement issues relating to piece-part procurement, long-lead bought-in hardware and heritage evaluation

4.1 Piece-Parts

When procuring piece-parts for a programme it is essential to make use of a procurement specification which is appropriately detailed. For example when procuring bearings ESTL has knowledge of recent procurements where for example:

- bearings were supplied from the manufacturers part-assembled with tie-wraps such that raceways were damaged by vibration during transit,
- manufacturers applied vibro-etched identification marks raised burrs on mating surfaces,
- corrosion is present on balls or raceways upon receipt (an increasingly frequent occurrence possible because some CFC-free solvent cleaning processes employ hygroscopic solvents which need careful management),
- bearings to be oil lubricated were supplied pre-coated with creep barrier on all surfaces including raceways, mating surfaces and the interior of intimate packaging.

4.2 Long-lead Bought-In Hardware

A recent long-lead procurement of flight standard ball-screw item resulted in a non-flight-compatible unit being delivered despite the use of a detailed procurement specification. On investigation it was found that though the local agent received the procurement specification it was not passed fully to the manufacturer. The agent simply passed the order on as a part number with an incomplete description of the hardware required (compared to the specification) and no packaging requirements.

In both the above procurement examples it is clear that IF such defects are detected upon receipt, lost programme time is the minimum consequence. However, if not detected possible consequences include costs in terms of increased development time or in-the-limit flight anomalies.

Lessons Learned: A detailed procurement specification must be used and where suppliers/agents are involved it should be verified in parallel that both they AND the manufacturer are fully aware of ALL requirements especially packing/cleaning and any other unusual or cirtical issues. Though most local suppliers/agents are good, experience suggests they cannot be fully relied on to echo all requirements back to the manufacturer. Therefore it is essential to ensure direct communication with both suppliers/agents and manufacturers to verify awareness of the full specification.

For bearings, ESTL has published a generic procurement specification document (Ref. 2) which aims to help minimise the time associated with generating a procurement specification and standardise the list of essential requirements without imposition of un-necessary requirements. At minimum this provides a valuable check-list of factors which should be considered and can be extended for use on other tribo-components.

4.3 Heritage Evaluation

A more critical issue is the evaluation of supplier-originated heritage data in order to predict performance in a new application. One example of this comes from a recent programme in which brushed motors were selected with a certain baseline brush material. Though the material had significant space heritage, in the new application the lifetest was not completely successful due to excessive brush wear.

Closer scrutiny revealed that the test plan developed for the new application had an unusually similar combination of air and vacuum running for a single deployment device (approximately 60:40). Furthermore it was clear that the supplier-originated wear data for the baseline brush material was unusual in that it showed no major differences between in-dry nitrogen (the supplier had no directly applicable in-vacuo data) and in-air operation. It is clear that some suppliers, particularly those for whom the space market is a small fraction of total business may not have access to specialised facilities or expertise required to properly carry out space standard verification or qualification of their products.

In this case, it became necessary to carry out an urgent and dedicated materials screening programme to source an alternative material for the new application. Brush replacement was then required with considerable schedule implications.

Lessons Learned:

a) Supplier originated test campaigns and data should be critically reviewed. In some cases it may be possible to highlight differences between supplier test and known performance margins for selected materials which should be investigated. Reputable suppliers do not seek to mislead, but if space is a small part of their total business they may not have the special resources needed to fully characterise their goods for a space customer.
b) For critical applications consider either involving consultants to review supplier data and methodologies or commissioning independent testing. Carried out by a dedicated test house.
c) Note also that even data obtained by test houses my not fully replicate a given application. Mechanical and tribological systems are complex and the only fully representative tests are those at unit level.

Finally in our discussion of procurement issues we have recently seen difficulties on a number of programmes where for cost reasons spare kit was not available at sub-assembly level. If subsequently issues arise with the development or flight units, the lack of a spare unit clearly will have development or flight schedule impacts. Notably also it seems the cost of rectification of any issues using actual development or flight hardware is almost always likely to exceed the cost of any spare hardware items.

Lessons Learned: ALWAYS MAINTAIN SPARES OF KEY ITEMS (Ignore the accountants they do not understand engineering risks!)

5. Development

5.1 Design Development and Verification

At the heart of any mechanism development programme there needs to be a technically sound and comprehensive design development and verification (DD&V) plan. In our experience however some organisations still regard this document as a necessary deliverable for the customers benefit alone.

Mechanisms perhaps more than any other spacecraft element are a huge risk to spacecraft performance, schedule and cost. The DD&V plan is the starting point for risk recognition, risk control by appropriate risk mitigation activities and the systematic and timely elimination of risks.

Early tests, even if the result is unexpected or negative remain a positive risk mitigation process.

Experience has shown that the most critical issues associated with mechanisms is the survival of random vibration and subsequent completion of a successful life test.

For the GOMOS SFA (flying on ENVISAT), it was decided that an early breadboard model was required, however this unit subsequently became a deliverable of the programme. For this reason the breadboard model was not subjected to an early vibration test and so the first vibration test was carried out on the later QM unit which suffered a structural failure of its flex-pivots. The failure presented a major cost- and schedule-impacting problem at a critical time in the programme.

The IASI programme in contrast also suffered a flex-pivot structural failure. However, probably as a result of a lesson learned in the above experience, the failure was encountered on the breadboard model. As a result both the thorough investigation and the recovery action was complete before the formal QM and FM was initiated.

Lesson Learned: The DD&V plan is a key document which is useful for both customer and mechanism developer and should be used as an essential risk register.

5.2 Cage Stability

In a number of applications using solid lubricated bearings cage wear and stability have been an issue. In order of increasing challenge examples are:

a) Where bearings experience 0g in-flight and a radial 1g vector for ground testing due to a need to test horizontal axis, for example GOMOS ACPM stepper motor on ENVISAT.

b) Spinning spacecraft with mechanisms remote from the axis. On MSG the Seviri Mirror Support Bearings (MSB) are subject to 4g axial acceleration throughout life. For GERB also on MSG, the Mirror Support Bearings are subjected to 16g radial acceleration (Ref. 3) with a lifetest requirement of 230 million revs.

In both MSG applications the challenge associated with the bearing cage was identified early in the DD &V plan and a number of development tests both on and off a dedicated centrifuge facility aimed at alternatives to cages (for the MSB application) and a reduced mass cage for GERB).

For GERB, lifetesting is still underway and the key requirements are to minimise cage wear debris and manage its egress from the bearing and retention within the bearing housing such that choking of the bearing (see Figure 2) cannot occur.

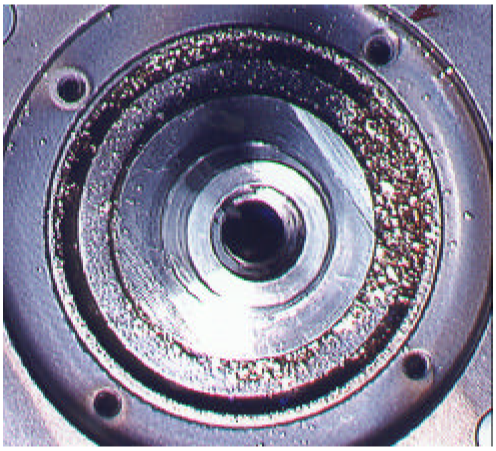

Figure 2 Debris-Choked Bearing Caused By The Combination Of High Cage Wear Under 16g And Insufficient Free Debris-Capture Volume To Allow Debris To Escape The Bearings

For GOMOS because the stepper motor had been previously used in vertical axis, the main challenge identified in the DD&V plan was believed to be the ballscrew life and therefore the stepper motor bearings were not tested in horizontal axis until after successful completion of the ballscrew lifetest. When the horizontal axis test in air was carried out it was found that in-air the cage was unstable under horizontal axis operation and generated an unacceptably high torque as a result. Therefore an urgent programme of cage development was carried out to identify a design which was stable in-air both horizontal and vertical axis.

Lesson Learned:

a) For solid lubricated bearings though cage design guidelines exist, cage wear and stability remain largely unpredictable from a practical viewpoint. If operation in any form of radial (≥1g) or axial (>1g) acceleration is to be applied during test or flight it is prudent to review and test proposed cage designs to verify acceptable behaviour at the appropriate operating speeds BOTH IN AIR AND IN-VACUO at an early stage in the development programme.

b) It should also be noted that there is some evidence (Refs. 4 and 5) that cage ball pocket wear rate is related to ball raceway contact stress (approximately proportional to $stress^4$) and this should be considered when evaluating heritage arguments for cage designs.

6. Build

6.1 Linear Stages

In a number of recent programmes a linear motion stage has been required. Examples include the MIPAS linear rails and more recently the translation stage for MIDAS. These are notoriously difficult to assemble and preload correctly due to their very high stiffness compared to typical support structures.

ESTL was contracted to carry out a tribological assessment of the MIDAS unit (Ref. 6) and identified the need for care during preloading therefore once contracted to build the unit some care was taken in defining a procedure which assured the preload was as uniform as possible over the length of travel. This procedure was used for the build of the EQM unit.

On test however, the unit exhibited a large torque variation between open and closed ends of the structure attributed to its relative flexibility at the open end.

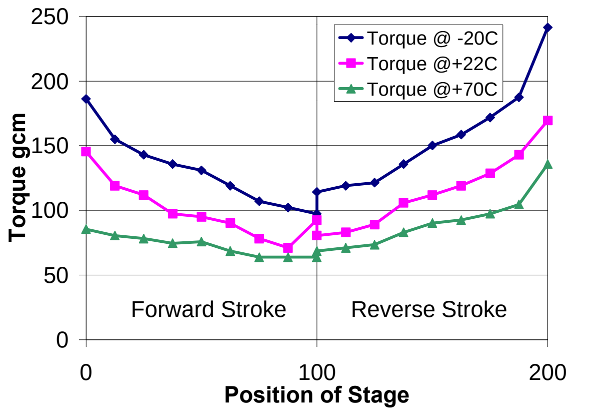

Figure 3 MIDAS Linear Stage Torque v Position and Temperature Showing Asymmetry ("0" and "200" are same position)

Furthermore during subsequent vibration the unit suffered a loss of preload. On inspection it became clear this was due to settling/deformation of the preload set-screws which are of much lower stiffness than the rails which they adjust.

As a consequence, the EQM was rebuilt with modified structure to provide more uniform distribution of stiffness and the preload setting was achieved using shim rather than the set-screws themselves (which were used only for adjustment). As a result a much more uniform torque characteristic was achieved and almost no changes occurred during vibration.

Lessons Learned:

a) Design/development sub-contractors should if appropriate to their background have inputs to the specification of analyses to be carried out by the lead-contractor.

b) Preloading procedures for linear stages should be capable of verifying accuracy of alignment at micron level over the entire length of the stage. The build technique or design must be capable of retaining the alignment through vibration.

7. Testing

In this section we present general lessons learned in vibration testing and some specific lessons concerned with peformance of ultrasonic piezomotors which are an attractive design solution requiring careful use and test.

7.1 Vibration Testing

The first vibration test is one of the most critical milestones in any mechanism programme. There are a number of common issues which arise due to schedule pressures as access to vibration facilities often needs to be pre-booked some time ahead. Typical problems include:

- Minimising pre-vibration functional tests such that it can be difficult to differentiate fundamental hardware problems from actual vibration-induced degradation effects.

- Failure to characterise the vibration facility cross-coupled input levels with the mechanism adapter supports. Many facilities apply rotational accelerations which convert to increased linear accelerations for adapters with off-set geometries.

- Compromising on the number of accelerometer channels, leading to inconclusive failure investigations if, as is often the case anomalies occur.

- Time consuming partial strip-downs to re-attach accelerometers. To minimise this, access for accelerometers should be a design consideration and accelerometers should employ back-up adhesive tape to avoid local damage in the event of mis-bonding.

- Vibration inputs and responses are not always well defined at the start of the test. Nevertheless, allowable and not-to exceed abort levels should be clearly defined and not negotiated during the test.

7.2 Thermal Vacuum Testing of Piezomotors

In late 1999 ESTL took part in the build and qualification test of a number of sub-assemblies of the MIDAS instrument (Ref. 6) which flies on Rosetta. This features one of the first flight applications of ultrasonic piezomotors which offer potential benefits of high powered output torque (per unit mass) and high detent torque when un-powered which is obviously very attractive during exposure to the launch environment. In this application a commercial-off-the-shelf Shinsei piezomotor was baselined which was rendered space-compatible by substitution of an appropriate grease and lead lubricated radial bearing. The motors used were first screened in air and selected for maximum output torque performance.

During the qualification phase, the motor performance was seen to degrade substantially with operation under thermal vacuum conditions. The reducing performance was subsequently found to be due to thermal degradation of the piezomaterial. Further investigations revealed that for thermal degradation begins at around 65°C for the material used. By continuous operation during the qualification phase internal temperatures exceeding this were easily reached.

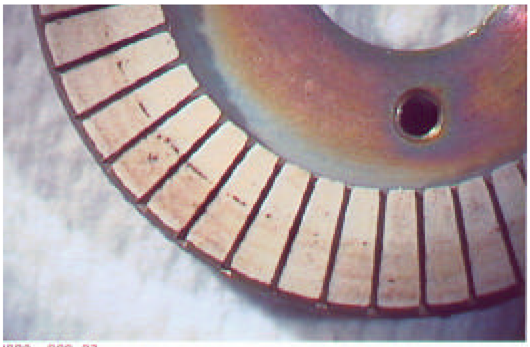

Figure 4 Piezomotor Segments After Successful Completion of Lifetest Showing Minor Evidence of Thermal Degradation.

In the MIDAS application it was fortunately possible to use the piezomotor for short periods with long cooling times between and so to avoid reaching the critical temperature for onset of thermal degradation. Therefore the qualification was repeated with a revised operating regime more representative of that to be used in flight and a lifetest was successfully completed.

Lesson Learned:
From a design viewpoint piezomotors are highly attractive, however piezo-material development seems currently not to permit operation beyond around 55°C (to allow margin) and internal thermal dissipation easily generates temperatures exceeding this. There is a need for an increased temperature capability piezo-material for use in ultrasonic piezomotors for space application.

8. Discussion and Conclusions

The complex nature of most mechanisms development programmes and their increasingly demanding specifications ensures problems will inevitably occur. This paper has identified a number of areas where past problems have been experienced together with consequences and solutions. It is the author's hope that at least some of the identified lessons learned arising from these experiences may be of value in current or future programmes.

From a mechanism developers viewpoint, it is extremely desirable to quantify and evaluate the obvious and less-obvious problems at an early stage in the development. Therefore access to heritage and experience from other programmes together with test facilities which can rapidly be focussed on finding solutions is an extremely valuable resource.
If the experience or facilities of external organisations (or internal specialists) are to be used for mechanism development then these should be closely integrated into the project team from an early stage. The aim should be to fully integrate this experience into the development programme rather than rely on it to provide a solution at the MRB.

Acknowledgements

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