Random Vibration Levels for the Herschel FPUs

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1. Introduction

The Herschel/Planck Payload Funding meeting at ESTEC on June 19 identified the following action:

JPL to elaborate on the problems raised on the vibration levels of the Planck LFI/HFI sorption cooler and the SPIRE bolometer arrays with reference to the original requirements – due 5 July 2002.

As this issue is one that is a major concern for several other subsystems, we are extending our response to cover the implications of the specified vibration levels for the instrument as a whole. It is also our understanding that the current qualification vibration levels are posing similar difficulties for HIFI and PACS.

The financial, schedule and scientific risks are such that we regard this as a major problem: however, we believe it is a problem that can be resolved to the satisfaction of all concerned by reassessing the current requirements while still being cautions and realistic.

The recent analysis by Alcatel (HP-2-ASPI-AN-0112.2.0_1) shows an order of magnitude margin between the random vibration levels expected a the FPUs and the IID-A specifications. We propose that the random vibration levels at the Herschel instrument FPUs be reduced by a factor of three with respect to the currently specified values. The rationale for this is discussed below.

As this issue is now a major cost and schedule driver for us, we would appreciate an early response to this note.

2. SPIRE FPU design

The overall thermal/mechanical design of the SPIRE FPU is dictated by the trade-off between the need to limit thermal loads and to ensure a mechanically robust system with the smallest possible overall mass. The challenges in so doing have been highlighted by SPIRE since the beginning of the project. We have endeavoured to keep the FPU mass as small as possible and have imposed strict mass and thermal budgets on all subsystems. The ability of the consortium to meet these stringent requirements within the constraints imposed by funding limitations has and continues to pose major difficulties and risks to the programme, which we regard as important to reduce.

With the design and development of the subsystems now well advanced, it is apparent that meeting the current stringent vibration levels is a significant problem for several subsystems, as described below.

3. Vibration qualification status of FPU Subsystems

Four major SPIRE subsystems have problems with the current levels, which are driving the design and the development/testing programme

3.1 Cooler

The baseline cooler design has 0.29-mm dia. Kevlar cords - needed to give enough margin on the hold time. Two STM units have been vibration tested at CSL. The SPIRE STM "survived", but the frequency signatures changed after the high sine test. Inspection showed one of the cords was partly damaged due to slipping at a pulley. The cord was replaced and the test sequence repeated with exactly the same result. A repeat test with 0.5 mm cord (as in the ESA TRP model) was successful.

Calculations show that this cord should fulfil the mechanical specification, but these calculations assume the cord does not slip in the pulley groove. It turns out it does under high vibration levels (40g). Although we are far from any resonant frequencies, the 40g acceleration was enough to move the evaporator (accelerations of up to 100g have been recorded once it starts to move due to slipping) and induce rubbing between the cord and the pulleys; as a consequence the cord ends up almost breaking (half the fibres damaged).

Use of the 0.5 mm cord for SPIRE results in heat lift and hold time that are still within specification but with reduced margin, as is summarised in the following table (note that SPIRE has requested a 4.5 K Level-1 temperature but the IID-A specification is < 6 K):

T structure (K)	Net heat lift (µW)
4.0	18.5
4.5	17
5.0	15.5
5.5	13.5
6.0	11

T structure (K)	Hold time (hrs)*	Average load (mW)
4.0	61.5	3.2
4.5	58.5	3.4
5.0	55.0	3.6
5.5	51.3	3.8
6.0	47.8	4.1

Notes:

1. A total 10-µW heat load from the BDAs and thermal strap system is assumed here. But this figure is in doubt itself because of the need to strengthen the BDAs and the thermal straps against vibration loads - this will further eat into the hold time.
2. In actuality, the SPIRE thermal model shows that for a 6-K temperature the combination of the higher 300-mK heat load and the higher Level-0 box temperature would result in a hold-time less than 45 hours.

If the hold time requirement is not met then there will be a loss of efficiency and/or lifetime due to cycling the cooler more often than is needed thermodynamically

3.2 BDAs and thermal straps

JPL are fabricating bolometric detector assemblies (BDAs) thermally isolated by Kevlar support fibres. This design must accommodate large accelerations, but must conduct a very small heat load, about 2 µW per unit from 2 K to 0.3 K, and retain mechanical alignment to 125 µm before and after vibration. In June 2001, it became apparent that the vibration level was a serious design issue. The input vibration specification at the base of the instrument lead to large accelerations on the BDA well outside current design capabilities. After 3 months of negotiation with ESA and the European SPIRE consortium, JPL agreed with the SPIRE Project a requirement of 100g static equivalent, based on assumed but unquantified damping in the instrument structure. This vibration level requires deep notching of the test input spectrum to gain extremal control, greatly complicating the test program. Furthermore, JPL must extrapolate the notching for performing vibration at low temperatures from room-temperature data. Finally, even with 100g static equivalent, the kevlar bands are very close to the allowed margin of safety on yield and coefficient of static friction.

The lack of margin requires JPL to perform extensive fatigue, creep, and friction testing on the Kevlar bands. This work is complicated by the fact that the Kevlar demonstrates load-dependent damping. Analysis also shows that that the mechanical load from the 0.3-K thermal strap may impose loads outside of the BDA mechanical margins. It is difficult for JPL to replicate exactly the mechanical loads from the thermal strap in tests at component level, leading to some risk during instrument-level testing. These complications have led them to spend considerable effort in evolving the BDA design over the last 12 months, and JPL still has not fully qualified the design to the 100g requirement (and to do so may result in a failure of the qual model BDA, which would immediately de-rail the delivery schedule for the CQM). The latest cold vibration tests reveal problem with significant displacement of the 300-mK stage measured after vibration.

JPL are continuing to devote major efforts to the mechanical qualification of the BDAs, as is essential as failure of any BDA could short 300 mK to 2 K and result in loss of the instrument. This has already had an adverse impact on JPL's budget and schedule. The estimated impact on JPL's costs last year is $2M, and further cost increases are imminent as mechanical qualification is now in progress. The BDA performance testing has been descoped to a minimal level in an effort to save money and maintain the necessary delivery dates. If significant effort is needed to address the problem, then descope in delivery schedule or number of arrays flown will be inevitable.

A test report on the BDA vibration measurements carried out so far is attached

It is expected that the random vibration input to the BDA during the system acoustic qualification test will be less than 0.05 g^2 Hz^{-1}, and the system acoustic test still will be conservative compared to flight. (This expectation is supported by acceleration data measured inside a dewar during the system acoustic test of the SIRTF spacecraft.) The expected fundamental resonance of the SPIRE instrument on the shaker is expected to be less than that of the BDA, which is around 200 Hz, and the instrument should therefore provide little or no amplification at the BDA resonance. Both the SPIRE Project and JPL regard changes to the current BDA design in order to meet the currently specified vibration requirements as unnecessary and wasteful of precious time and money.

The recommendation from JPL experts was to base the instrument test notching on the predicted flight (or acoustic test) maximum random vibration forces, using the methodology in NASA handbook HDBK-7004. This would result in somewhat deeper notches than those previously negotiated with ESA, which were based only on not exceeding the quasi-static structural loads

We have asked JPL to proceed with a conservative test programme pending revision of vibration level requirements, to minimise the risk of damaging the BDA qual model thereby causing a serious schedule and/or descope problem.

Having considered the available test data and analysis, we have agreed the following with JPL:

- The BDAs will be warm vibrated with a flat spectrum in the 100-300 Hz range at a level of 0.05 g^2 Hz^{-1}, which corresponds to current level specified at the optical bench.

- Subsequent tests will be done at higher levels increasing in steps of about a factor of 2 up to 0.2 g^2 Hz^{-1} or until failure occurs. This test process will characterise the vibration levels that the unit can survive.

- We will need to work towards defining the vibration tests that can be regarded as sufficient for qualification before the instrument-level vibration. The strategy for cold vibration qualification of the BDA is a difficult issue and is still under consideration; it will depend on further analysis, the outcome of these tests, and on progress towards reducing the required levels.

- It is planned to implement force gauges mounted at the FPU feet during instrument-level testing to allow the correct notching to be implemented (in accordance with the policy agreed last year with ESA).

The thermal strap which links the ^{3}He cooler to the five BDAs system is also a single point failure for SPIRE. The design is complex because of the physical separation of the arrays, the need for light-tight entry to the 2-K enclosure, and the stringent thermal budget available in order to minimise the heat load onto 0.3 K. Analysis presented at the Thermal Strap system DDR on July 10 showed small, possibly negative margin, especially in torsional modes that are difficult to suppress. Tests on a redesigned prototype are pending. The development philosophy must be to favour mechanical integrity over thermal performance, possibly further adversely affecting the ^{3}He cooler performance.

4. SMEC

An analysis has been done by the pivot manufacturer, BE Systems, and the results are documented in the attached note (LAM/F02/045). The worst-case loading case is that of random excitation in the lateral direction, which leads to a maximum radial force calculated at 938 N, which is nearly a factor of four higher than the acceptable value of 250 N (see attached note, Table 8 and Section 9). Significant redesign will be needed unless STM tests show lower than expected vibration levels at the SMEC location in the instrument, and the required changes may not be compatible with the current FPU design. The SMEC development plan thus represents a very high risk: at present there is no technical solution identified and the viability of the SPIRE FTS is therefore in question.

5. Conclusions and recommendations

1. We propose that a meeting (ESA/Instruments/Industry) be set up without delay to discuss the vibration levels issue as a matter of the highest urgency for all three Herschel instruments. If this problem is properly addressed now, it will save everyone a great deal of trouble later on.

2. Current subsystem development programmes continue to be driven technically and financially by the need to meet the current vibration levels. **Cost over-runs have already occurred and are continuing** (and are partly responsible for the funding difficulties recently highlighted).

3. Accommodating the current vibration levels is **certain** to require compromise to the scientific performance of SPIRE and Herschel through boiling off too much helium by recycling the cooler more than is needed.

4. Taking into account the success-oriented programme for subsystem delivery and for STM-level qualification, the **current FPU vibration levels pose major risk to unit-level and STM system-level programmes**.

5. Any failure at unit or instrument level will inevitably delay delivery and may result in descope of instrument thermal and/or scientific performance. Possibilities are: removal of some of the detector arrays, reduction in Herschel lifetime due to more frequent cooler recycling; restriction of the spectral resolution of the FTS.

6. Given the results of industry's analysis, a significant relaxation of vibration levels would seem reasonable, and such **a reduction in the levels is essential if SPIRE is to be delivered on time**. The benefits would be:

    - a credible margin can be maintained wrt the calculated levels and at the same time providing more achievable levels for the instruments;
    - the risk of late instrument delivery and/or descope of SPIRE's scientific capabilities will be substantially reduced;
    - the severe financial pressure on subsystem groups, and consequent impact on the level of subsystem and system-level testing that can be carried out, will also be reduced;
    - more science can be done with Herschel as the SPIRE and PACS coolers can be recycled less often.

7. It will be senseless for all of us to continue to spend more and more time and money working to solve what we expect to be a non-problem when we know we will need those resources for more real problems if we are to meet the schedule.

8. We expect that it will take some tome to reach a formal resolution of this issue. In the meantime **we must proceed with our qualification programme at subsystem and instrument STM level**. Our approach to this will be as follows - and we request ESA to comment on this approach:

- **Cooler:** We will instruct Grenoble to provide a cooler for the STM/CQM with the thinner 0.29-mm diameter Kevlar cord
- **Thermal straps:** We will test the units to levels consistent with the current requirements to characterise the ultimate survivability, but will not regard a failure at such levels as requiring a redesign.
- **BDAs:**
  - As noted above, we have advised JPL to proceed cautiously in testing the BDA qual. model, because if this unit breaks during testing, it will set their programme back by several months and also result in a big cost over-run.
  - We **urgently** need to define more realistic qualification levels for JPL in the near future, and this requires some guidance from ESA. These levels should be consistent with the BDA as designed, which we are confident can actually withstand an Ariane launch). It is essential that we get some indication from ESA/industry as to what the new levels are likely to be. Otherwise, we will be in a difficult position in that JPL will not have agreed levels for their qualification programme which, for schedule, cost and formal NASA review reasons, must take place very soon.
- **SMEC:**
  - The STM will be built with solid bushes in place of the flex pivots. Vibration levels will then be measured during the instrument level warm vibration test. These measurements will form the basis of the unit level qualification vibration test. Flight standard pivots will be used in the qualification model.

Attachments:

1. BE Systems report on SMEC vibration response.
2. BDA vibration test report.