The HIFI OD-81 Anomaly

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***Abstract*— On Monday 3rd of August 2009 the Mission Operation Center (MOC) reported that Herschel-HIFI was found in an undocumented state since 22:43Z on August 2nd during otherwise nominal execution of a red-shifted C+ observation in band 7b. The instrument no longer responded to HK requests and commands for the LO subsystem and communication between the Instrument Control Unit (ICU) and the Local Oscillator Control Unit (LCU) had clearly been lost. At the same time the HEB mixer in band 7 had changed from a nominally pumped to a completely under-pumped state and the primary power consumption of the LCU had dropped from a nominal current of 2.5A to 0.36A only.**

In this paper we present the results of the HIFI OD-81 anomaly investigation from early symptoms to a fully consistent failure scenario offering an explanation for what most likely had happened in space. This paper summarizes the key findings obtained from a detailed telemetry analysis and timing reconstruction, electrical circuit simulations, laboratory tests on a representative hardware model and component level tests, as well as software code analysis and simulation. We conclude by a description of the identified recovery solution and the implementation of risk mitigation measures protecting the instrument during future operations.

I. Introduction

A. HIFI Block Diagram

The Heterodyne Instrument for the Far-Infrared (HIFI)[1] on board of ESA's cornerstone mission Herschel[2] launched on the 14th of May 2009 is a high resolution spectrometer operating in the 480-1910 GHz frequency range. A schematic block diagram is shown in Fig. 1. The Instrument Control Unit (ICU) interfaces with the spacecraft bus and divides up the telecommands received from the spacecraft into unit level commands distributed over a serial interface and collects housekeeping from all units and science data from a High Resolution Spectrometer (HRS) and Wide Band Spectrometer (WBS). The spectrometers operate on two orthogonal polarizations H and V whose inputs are connected to the IF amplifier outputs of mixer units (SIS and HEB) where the astronomical signal has been down-converted to a 4-8 GHz IF band. The Local Oscillator (LO) signal is generated in the Local Oscillator Unit (LOU) which is based on direct multiplication and power amplification of a Ka-band synthesizer referred to as the Local oscillator Source Unit (LSU). The LO subsystem (LOU + LSU) is controlled via the Local oscillator Control Unit (LCU) providing the bias supplies for the LO hardware and secondary power to the LSU.

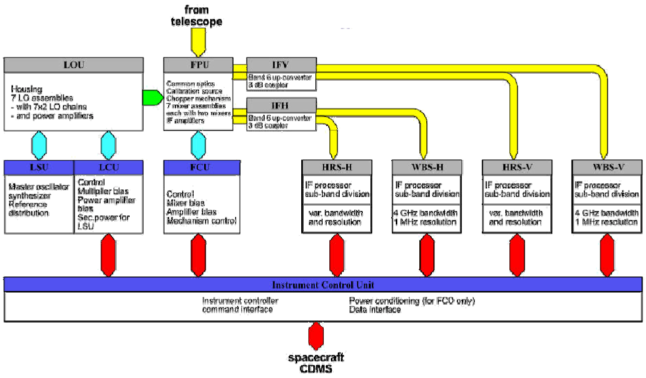


Fig. 1 Schematic block diagram of HIFI illustrating the functional division between the Local Oscillator and Focal Plane Unit subsystems, the spectrometers and the control units.

B. Local oscillator Control Unit (LCU) Breakdown

The primary power to the LCU is supplied through the spacecraft Power Distribution Unit at a bus voltage of +28V. The prime and redundant circuits of the LCU as well as the ICU can be selected by a dedicated Latching Current Limiter (LCL) that connects the spacecraft bus to the desired unit and provides over-current protection from the spacecraft point of view. It is worth mentioning here that it is not possible to configure the instrument in a hybrid mode where prime and redundant units are in mixed use. Either all prime or all redundant units can be switched on. The redundancy of the FPU and spectrometers are implemented in the H and V polarization and do not have separate prime and redundant interfaces with the spacecraft.

The LCU electronics contain four groups of DC/DC convertors generating all the necessary supply voltages for the digital electronics, bias circuits, relays, heaters, and secondary power circuits. The LCU contains a micro-controller in which the LCU software runs and safety tables for LO tuning are maintained. A schematic block diagram is shown in Fig. 2. In the upper left corner the spacecraft primary power interface is shown followed by a low-frequency ripple filter which was added during spacecraft integration to reduce current ripple as a result of primary current oscillations between the LCL and LCU. Within the LCU the +28V is filtered and further distributed to four groups of DC/DC converters. One of those groups, consisting of convertors DCDC1, DCDC2, DCDCHRS1 and DCDCHRS2 is only powered when the LO is providing RF power. In standby mode these units are off reducing the overall power consumption of the unit. Mode transitions between nominal and standby can be controlled through a standby switch/relay.

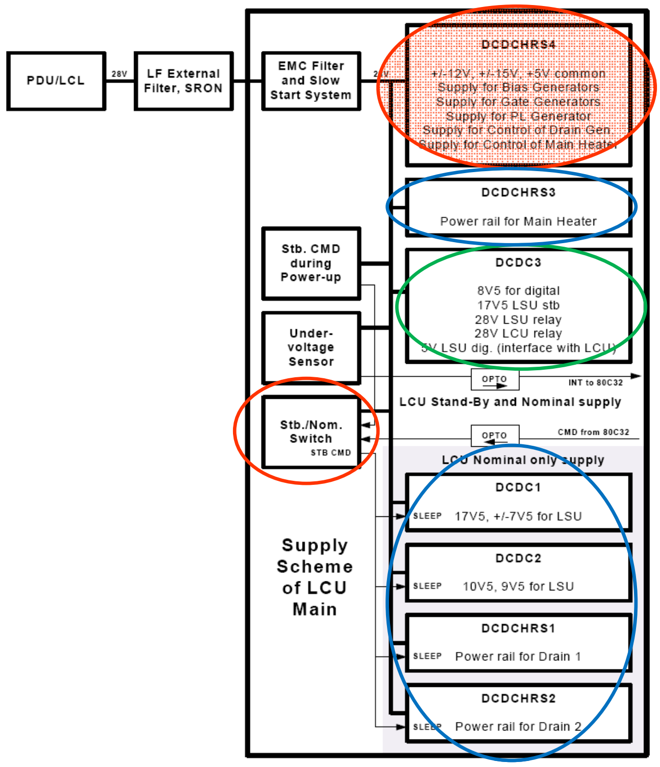
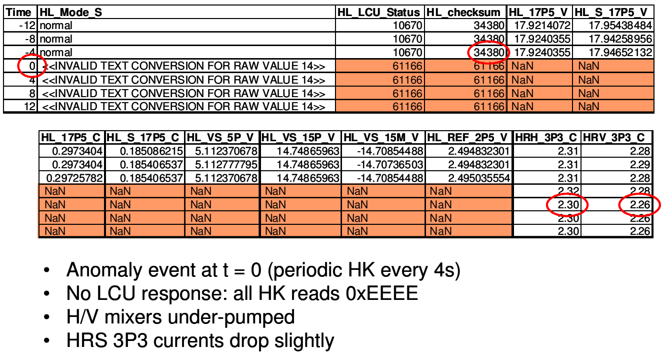


Fig. 2 Electrical block diagram of the Local oscillator Control Unit (LCU) showing the groups of DC/DC convertors.

II. Event Reconstruction

A. *LCU Failure 2009-08-02 T22:43:00Z*

During DTCP (daily ground contact) of August 3rd (OD81) the LCU was found in an unknown mode 14 since 2009-08-02 T22:43:00Z (Fig. 3 and 4). From that moment on no response from the LCU to periodic HK requests (0xEEEE) and commands was received anymore (See Fig. 3). The LCU, LOU and LSU temperatures started to drop immediately. Spacecraft heaters were immediately switched on in an attempt to compensate the drop in temperature. The primary supply current dropped from 2.5A, corresponding to nominal operation of the LCU, to 0.36A from one to the next periodic HK reading, whereas the primary supply voltage remained constant all the time. The active band at the time of failure was band 7b tuned at a frequency of 1893.16 GHz in an on-the-fly mapping observing mode.



Time	HL_Mode_S	HL_LCU_Status	HL_checksum	HL_17P5_V	HL_S_17P5_V
-12	normal	10670	34380	17.9214072	17.95438484
-8	normal	10670	34380	17.9240355	17.94258956
-4	normal	10670	34380	17.9240355	17.94652132
0	<<INVALID TEXT CONVERSION FOR RAW VALUE 14>>	61166	61166	NaN	NaN
4	<<INVALID TEXT CONVERSION FOR RAW VALUE 14>>	61166	61166	NaN	NaN
8	<<INVALID TEXT CONVERSION FOR RAW VALUE 14>>	61166	61166	NaN	NaN
12	<<INVALID TEXT CONVERSION FOR RAW VALUE 14>>	61166	61166	NaN	NaN

HL_17P5_C	HL_S_17P5_C	HL_VS_5P_V	HL_VS_15P_V	HL_VS_15M_V	HL_REF_2P5_V	HRH_3P3_C	HRV_3P3_C
0.2973404	0.185086215	5.112370678	14.74865963	-14.70854488	2.494832301	2.31	2.28
0.2973404	0.185406537	5.112777795	14.74865963	-14.70736503	2.494832301	2.31	2.29
0.29725782	0.185406537	5.112370678	14.74865963	-14.70854488	2.495035554	2.31	2.28
NaN	NaN	NaN	NaN	NaN	NaN	2.32	2.28
NaN	NaN	NaN	NaN	NaN	NaN	2.30	2.26
NaN	NaN	NaN	NaN	NaN	NaN	2.30	2.26
NaN	NaN	NaN	NaN	NaN	NaN	2.30	2.26

- Anomaly event at t = 0 (periodic HK every 4s)
- No LCU response: all HK reads 0xEEEE
- H/V mixers under-pumped
- HRS 3P3 currents drop slightly

Fig. 3 No response from LCU to periodic HK requests

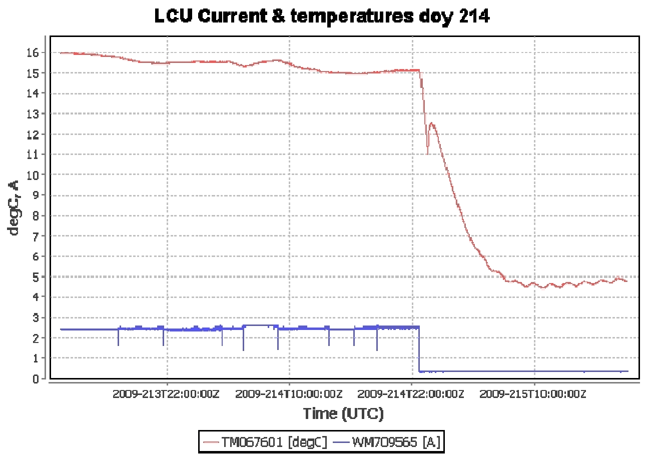


Fig. 4 Graphical illustration of the event recorded on OD-81. In blue the primary current consumption is shown, whereas the LCU temperature profile is indicated in red.

Inspection of the periodic LCU HK revealed that the LO power dropped from one to the next HK reading leaving the HEB mixer in an unpumped state (see Fig. 5). Prior to the event the conditions of the LO hardware as mimicked by the LCU HK were stable at the bit resolution level. The change occurred within one HK cycle of 4s. The drop in LO power was also confirmed by the HRS 3P3 current HK reading which is indicative of the IF power level of the mixer which in turn depends on the LO power received by the mixer. Just prior to the event the conditions at the LO hardware were completely stable (at the bit resolution level), reflected by very stable LCU analogue HK readings, primary supply current readings as well as HEB mixer and HRS 3P3 current HK readings. No action directed to the LO chain was going on at the time of the event.

B. *LCU Switch-off 2009-08-04 T15:20:00Z*

During DTCP of the 4th of August 2009 (OD83) the LCL for the LCU was opened removing the primary power from the unit. This was done in between the switching points of the thermal regulation cycle of the spacecraft. From the LCU and LSU temperature profiles with respect to time it was concluded that the dissipation of the LCU as well as the LSU had dropped. This was concluded on the basis of the changed temperature slope and duty cycle of the thermal regulation loop as shown in Fig. 6. When switching the LCU off the HRS 3P3 current increased from 2.2 to 2.6A yielding a yellow flag for the HRS as can be seen in the upper plot of Fig. 6. In turn the HRS-H and –V were switched off as well. The increase of 3P3 current was assigned to the loss of the 10 MHz reference signal supplied by the LSU. HIFI was hence left in a hybrid state with the all units powered except for the LCU, LSU and HRS.

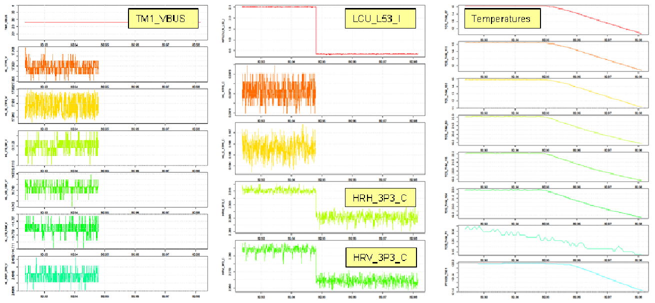


Fig. 5 HK traces illustrating the sudden drop of primary supply current (top-middle) whereas the bus voltage remains unchanged (upper-left). The change of mixer current and IF power level was also detected by the HRS 3P3 current HK (IF processor). In the right column the change of temperatures following the event can be seen.

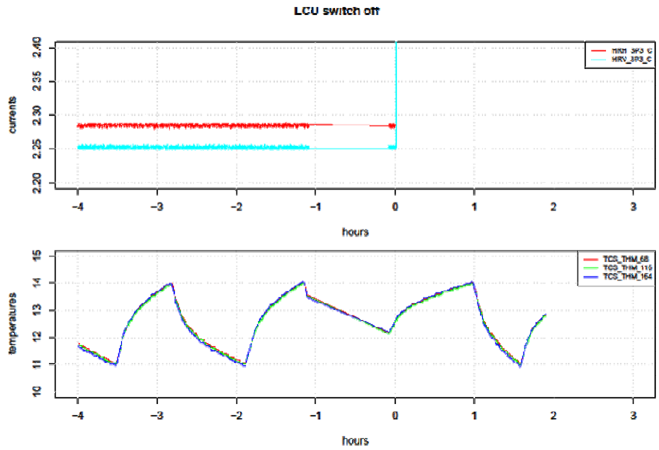


Fig. 6 Change of the HRS IF processor current consumption (3P3) and changed temperature profile of the LSU spacecraft panel when the LCU was switched off.

C. HIFI Switch-off 2009-08-07 T15:15:00Z

For spacecraft thermal management reasons it was finally decided to switch off HIFI entirely during DTCP of the 7th of August (OD86). The final LOU, LCU and LSU temperature levels showed to be consistent with the values observed during the initial switch-on of HIFI after launch on May 24th.

D. Initial Evaluation LCU Power Consumption

Using the refurbished QM model of the LCU (IMD-3) an initial evaluation of the power consumption of the electronic modules was made in order to explain the low primary power consumption of the LCU (0.36A in Fig. 4). The main conclusion was that only a failure in DC-DC convertor HRS-4 in combination with a switched standby relay as shown in Fig. 2 would explain such low power consumption. All other combinations of single failures in DC-DC convertors would lead to higher power consumption than observed. Simulating a failure in HRS-4 in the lab setup and switching the LCU off and on again showed that the communication would be restored, analogue HK would be missing (zero readings, fixed raw values ADC) and a current below 0.4A would be drawn.

E. HIFI Restart 2009-08-10 T15:30:00Z

During DTCP of August 10th (OD89) a HIFI restart attempt was made. After closing the LCL for the LCU the primary supply current stabilized at 0.36A as shown in Fig. 7. The 10 MHz reference supplied by the LSU re-appeared reflected by the expected drop in the HRS 3P3 currents. Communication was fully restored and the LCU was found in standby mode after the boot procedure. The LCU checksum was in agreement with the expected value for the firmware (0x8D04) loaded from the on-board PROM confirming the integrity of the LCU memory. The analogue HK values were zero with a fixed raw value of 0x4000 in agreement with a non-powered ADC.

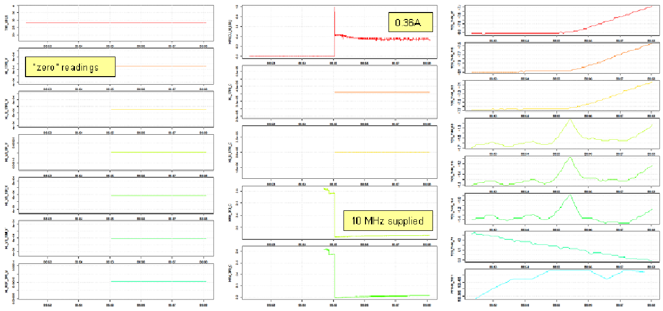
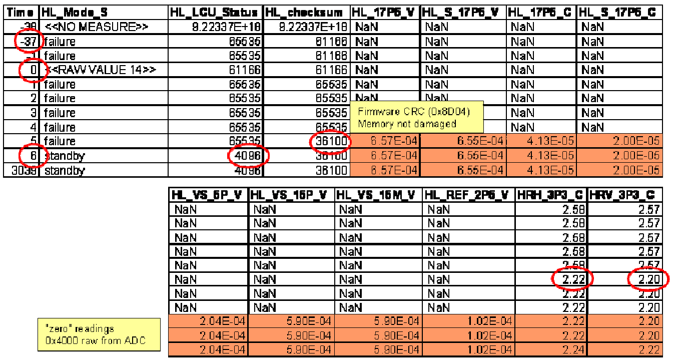


Fig. 7 HK charts centered on the HIFI restart attempt. In the left column "zero readings" of all analogue HK channels are shown. In the middle column the top plot the primary current consumption converges at 0.36A and the 10 MHz signal is provided again as shown by the 3P3 current profiles. In the right column the rising unit temperatures are shown.



Time	HL_Mode_S	HL_LCU_Status	HL_checksum	HL_17P6_V	HL_S_17P6_V	HL_17P6_C	HL_S_17P6_C
-38	<<NO MEASURE>>	9.22337E+18	9.22337E+18	NaN	NaN	NaN	NaN
-37	failure	65535	61166	NaN	NaN	NaN	NaN
-1	failure	65535	61166	NaN	NaN	NaN	NaN
0	<<RAW VALUE 14>>	61166	61166	NaN	NaN	NaN	NaN
1	failure	65535	65535	NaN	NaN	NaN	NaN
2	failure	65535	65535	NaN	NaN	NaN	NaN
3	failure	65535	65535			NaN	NaN
4	failure	65535	65535			NaN	NaN
5	failure	65535	36100	6.57E-04	6.55E-04	4.13E-05	2.00E-05
6	standby	4096	36100	6.57E-04	6.56E-04	4.13E-05	2.00E-06
3039	standby	4096	36100	6.57E-04	6.55E-04	4.13E-05	2.00E-05

Firmware CRC (0x8D04)
Memory not damaged

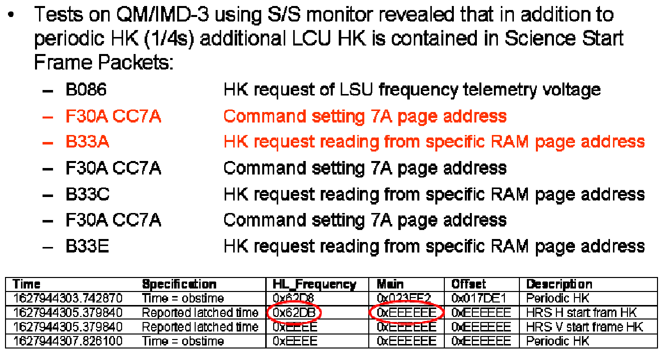
HL_VS_6P_V	HL_VS_16P_V	HL_VS_16M_V	HL_REF_2P6_V	HRH_3P3_C	HRV_3P3_C
NaN	NaN	NaN	NaN	2.58	2.57
NaN	NaN	NaN	NaN	2.58	2.57
NaN	NaN	NaN	NaN	2.58	2.57
NaN	NaN	NaN	NaN	2.58	2.57
NaN	NaN	NaN	NaN	2.58	2.57
NaN	NaN	NaN	NaN	2.22	2.20
NaN	NaN	NaN	NaN	2.22	2.20
NaN	NaN	NaN	NaN	2.22	2.20
2.04E-04	5.90E-04	5.90E-04	1.02E-04	2.22	2.20
2.04E-04	5.90E-04	5.90E-04	1.02E-04	2.22	2.20
2.04E-04	5.90E-04	5.90E-04	1.02E-04	2.24	2.22

"zero" readings
0x4000 raw from ADC

Fig. 8 HK table extract near the HIFI restart attempt. At t = -37s the HK is activated, but the unit is still off and no valid HK is available, at t = 0 the unit is switched on and after the boot procedure the correct firmware CRC is echoed at t=5. From t=6 the LCU responds to HK requests in standby mode and "zero" readings for the analogue HK are observed. During the boot procedure the 3P3 current of the HRS IF processor drops indicating the presence of the 10 MHz signal provided by the LSU.

F. Timing reconstruction

In addition to the periodic HK, collected every 4s, a number of specific HK readings from the LCU were made as part of the observing mode at the time of the failure. At the start of each spectrometer integration a specific sequence of LCU commands and HK requests was sent to fill the start-frame packet of the science data. It was found that communication was lost before power was lost. At the start of each spectrometer integration the commands as shown in Fig. 9 are sent to the LCU with 3ms separation in time. The moment where communication was lost could be confined to a time interval of 6 ms connected to the execution of a specific command (F30A CC7A) and following housekeeping request (B33A). From that moment in time the HEX pattern 0xEEEE was found in the data which is the default HK value substitution by the ICU for an uncompleted HK request.



- Tests on QM/IMD-3 using S/S monitor revealed that in addition to periodic HK (1/4s) additional LCU HK is contained in Science Start Frame Packets:

– B086	HK request of LSU frequency telemetry voltage
– F30A CC7A	Command setting 7A page address
– B33A	HK request reading from specific RAM page address
– F30A CC7A	Command setting 7A page address
– B33C	HK request reading from specific RAM page address
– F30A CC7A	Command setting 7A page address
– B33E	HK request reading from specific RAM page address

Time	Specification	HL_Frequency	Main	Offset	Description
1627944303.742870	Time = obstime	0x62D8	0x023EE2	0x017DE1	Periodic HK
1627944305.379840	Reported latched time	0x62DB	0xEEEEEE	0xEEEEEE	HRS H start fram HK
1627944305.379840	Reported latched time	0xEEEE	0xEEEEEE	0xEEEEEE	HRS V start frame HK
1627944307.826100	Time = obstime	0xEEEE	0xEEEEEE	0xEEEEEE	Periodic HK

Fig. 8 Sequence of commands associated with a start science frame packet. It was found that in between execution of the command F30A CC7A and HK request B33A communication had been lost confining the moment of the event to a time interval of only 6 ms.

Making use of the data collected by the HIFI spectrometers during the integration interval where loss of LO power took place it could furthermore be reconstructed that permanent loss of communication happened 1.6s before the LO power was lost. The observing mode consisted of 3s integrations: 3 times 1s integrations for the HRS and one 3s integration for the WBS.

By considering the total power in an IF spectrum for A) a fully pumped mixer prior to the event, B) an integration during which drop of LO power occurred and C) a fully underpumped mixer after the event a linear interpolation scheme was used to reconstruct the time of the event relative to the start of the integration sequence (see Fig. 9). For the WBS as well as the HRS a consistent number of 1.58s was found. The validity of the method was verified by using the lab setup consisting of the QM/IMD-3 LCU unit, a so-called subsystem bus monitor which was used to monitor and trigger on traffic on the serial interface between the ICU and control units and a noise source connected to a fast switch.

We therefore came to the important conclusion that the whole sequence of events connected to the LCU failure started with loss of communication and only 1.6s later with loss of LO power. This strongly suggested that loss of communication was not caused by a failure and reversed the intuitive order of cause and effect.

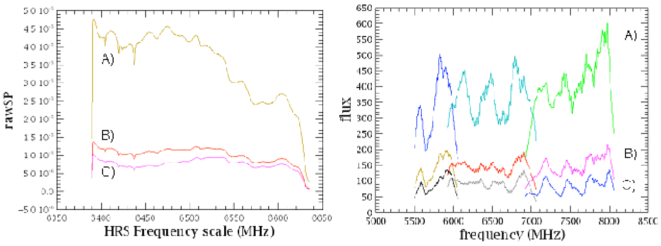


Fig. 9 Raw HRS and WBS spectra corresponding to A) fully pumped mixer, B) integration during which failure occurred and C) completely underpumped mixer.

G. *Key Symptoms of the LCU Event*

Reconstruction of the LCU event showed that the failure scenario must be consistent with all of the following key symptoms:

- After the event the LCU was found in a state with low power consumption drawing 0.36A primary supply current
- After the event the LCU was found in a state where the standby relay had been switched
- During the sequence of events eventually leading to the LCU failure communication was lost and only 1.6s later the RF power was lost.

III. Hardware Investigations

A systematic Failure Mode and Effect Analysis (FMEA) was made on the basis of available electrical circuit diagrams. This FMEA focussed on the main effects summarized above in II.G. The FMEA included the effect of the LCU interfaces as well as environmental conditions (temperature, radiation). The failure of DC/DC convertor HRS-4 has been analysed in several ways:

- Design inspection by DC/DC convertor experts from ESA (Ferdinando Tonicello) and JPL (Ted Fautz)
- Part stress analysis by JPL supported by SRON
- Circuit simulations by SRON

The FMEA showed that there is a group of component failures that may cause the failure effect for DC/DC convertor HRS-4 as observed in the mission. This group of components contains all secondary rectifier diodes, an UC1825 PWM controller and some resistors and capacitors.

Extensive testing was undertaken on the QM/IMD-3 unit in the lab to simulate the effect of these potential component failures and to determine the corresponding electrical conditions. Many partial failure scenarios starting with a component failure in DC/DC convertor HRS-4 have been considered but have all been rejected because:

- Loss of communication could not be explained within hardware constraints

- Loss of LO power would be rather immediate (<< 1.6s) or precede the moment of loss of communication

A scenario starting with a component failure was therefore considered not to be consistent with the observed behaviour and a component failure leading to failure of DC/DC convertor HRS-4 appeared to be a consequence and not the root cause of the anomaly.

Design inspection by Ferdinando Tonicello and subsequent tests finally revealed that a group of diodes of type 1N5819 were subject to electrical conditions that exceeded their absolute maximum ratings . There are 16 diodes in the HRS-4 DC/DC convertor and 4 in the DCDC2 convertor. All these diodes are secondary rectifier diodes that were identified in the FMEA as possible causes of the failure effect as observed in the mission. No other components were found with any electrical or thermal stresses outside acceptable ranges.

In Fig. 10 we show the secondary diode configuration. Diodes D1 and D2 are of type 1N5819. It was found that the leakage inductance of the transformer in series with the diode capacitance formed a resonant LC circuit resulting in a very short spike/overshoot every time the diodes switch from forward conduction to reverse operation. The 16 diodes in the HRS-4 converter are nominally subjected to reverse voltage peaks of ~54V, while their absolute maximum reverse voltage is specified as 45V. The duration of the voltage peaks is ~50 ns at a repetition rate of 65 kHz (0.3% duty cycle).

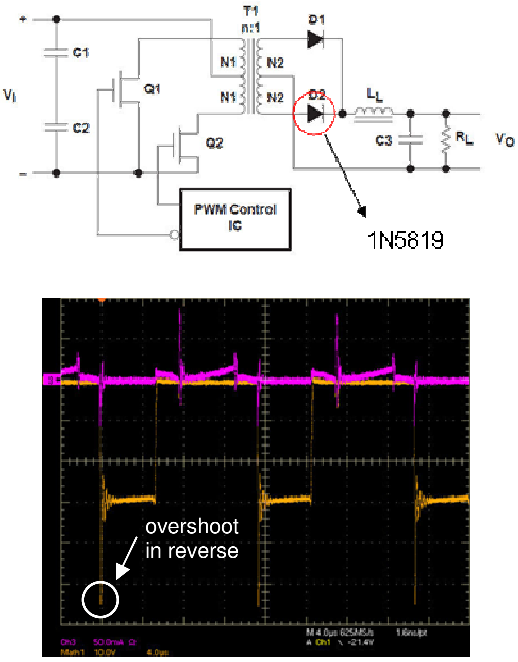


Fig. 10 Reverse voltage overshoot across the 1N5819 secondary rectifier diode.

The level of the peak voltage only depends on the input voltage of the HRS-4 converter. This voltage is usually 27V due to voltage loss across cables and LCU Ripple Filter. An overshoot on the HRS-4 input voltage occurs when the current drawn by the LO subsystem changes significantly (i.e. during mode transitions, band changes, etc). Generally these overshoots are about 2V (planned cases), only in case of a sudden transition from nominal to stand-by mode (unplanned) the overshoot can be as high as 4V. The voltage peaks across the diodes reach 58V or 62V respectively.

Tests performed on a limited number of diodes showed an average reverse breakdown voltage of 59V, so it is likely that breakdown occurs during such changes in LO subsystem activity. Breakdown is considered as the primary cause for damage and ultimately failure of these diodes.

For that reasons dedicated component level tests have been performed on representative flight quality devices (see Fig. 11). An endurance test of over 2000 hrs with short repetitive reverse current pulses up to 1A avalanche current did not kill any Schottky diode. On the other hand tests on commercial diodes immediately killed one device at only moderate conditions whereas another could not be killed at all. All of this suggests a failure mode in which the reverse current finds a local destructive path in contrary to a global thermal breakdown of the entire junction. Evidence was furthermore found in literature that the failure mechanism is threshold driven and can be avoided by reverse energy screening of flight devices.

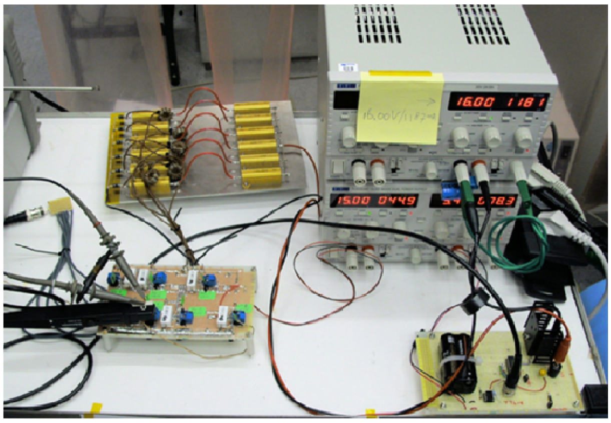


Fig. 11 Repetitive pulsed-stress setup addressing failure mechanism of 1N5819 diodes.

IV. SOFTWARE INVESTIGATIONS

In parallel of hardware investigation a thorough software investigation program was set up. The program concentrated on:

- routines in the LCU software that invoke the standby relay
- identification of program execution paths taking 1.58s before switching the standby relay
- possible ways to loose communication

It was found that only a limited number of software routines actually invoke the standby relay:

- in the start procedure (software reset) which is initiated when:

  - the LCU is powered on
  - executing a reset command from the ICU
  - returning from an undervoltage protection (emergency shutdown) interrupt service
- in the undervoltage protection (emergency shutdown) interrupt service
- in the procedure of executing the standby command from the ICU (standby transition)
- in diagnostic testing procedures still present in the program memory but not being used

Regarding the delay between loss of communication and LO power it was identified that only the start procedure takes considerable execution time and could add significantly to the 1.6s delay observed during the mission. This procedure takes about 1.2 to 1.3s during which the LCU firmware in the PROM is copied into RAM and the standby relay is switched in the end as a final initialization step.

Regarding the loss of communication many analyses and tests have been executed trying to simulate permanent loss of communication. Only in two cases permanent loss of communication was demonstrated:

- When the 28V voltage is interrupted (removed) internally for a specific duration such that the system restarts. This is however not compatible with the observed 1.6s delay as the undervoltage protection interrupt service would have acted immediately removing the LO power with virtually with zero delay. Moreover the LCL would have tripped in view of the required duration.
- When the program makes an unexpected “jump to zero”. If program execution somehow jumps to address zero, the start procedure is being executed, which leads to a switch of the standby relay after 1.2 to 1.3s, but in this case also to permanent loss of communication.

During the confined time interval where loss of communication was observed either a command was being handled or a HK request was being executed. A detailed analysis of the code and subroutines executed as part of handling the command (F30A CC7A) and the HK request (B33A) was made. In the code related to handling the command a memory area was identified whose corruption could have lead to an unexpected jump in the program eventually leading to a jump to address zero. Single bit-flips in that memory were simulated by patching the LCU software and executing the command and HK request sequence. Of order 40 bitflips out of 800 tested cases could lead to the observed sequence of permanent loss of communication and a standby relay switch after more than one second (1.3-1.6s). The statistics also showed that in 5 individual bit-flip cases both the observed sequence as well as the 1.6s delay could be reproduced.

A Single Event Upset (SEU) analysis confirmed that the SEU rate for the memory chip used is approximately once per 5 days. The probability that a SEU causes the observed behaviour ranges from once per year to once per 90 years (and even once per 700 years when the delay of 1.6s is exactly to be reproduced).

V. Proposed Failure Scenario

Putting all investigation results together we found only one consistent scenario that could explain the full sequence of events as observed on OD-81:

- A single event upset corrupted the memory at the location of the program code of a particular command or HK request.
- This bit-flip caused loss of communication when that specific code was called as part of a scientific integration sequence.
- Eventually the processor resumed program execution at address 0 where the start procedure was activated
- After 1.6s the standby relay was switched
- The corresponding load transient caused a voltage overshoot on the 28V bus.
- In the presence of the intrinsic pulsed-stress condition on the secondary rectifier diodes, this overshoot became fatal for one of the devices taking DC/DC HRS-4 down.
- The whole sequence of events left the unit in standby mode, with permanent loss of communication and low primary current consumption of 0.36A.

VI. Risk Mitigation Measures and Future Operations

Since further use of the HIFI prime units appeared pointless it was recommended to continue preparations for switching on and using the redundant units of HIFI. Before this could be done the following risk mitigation measures had to be taken in order to avoid a repetition of a similar component failure:

- Reduce load steps, avoid significant and unnecessary primary current transients associated with instrument mode transitions by changing the operational procedures and a modified LCU state definition
- Avoid a cold start of the LCU, operate the unit between 10 and 30ºC to keep the stress on the rectifier diodes within tested ranges
- Disable the LCU program code that can switch the standby relay after execution of the boot procedure
- Perform explicit and regular checksum calculations after each observation verifying the integrity of the LCU memory in order to timely capture a SEU. Abort operations when a corruption is detected.

At the time of reporting and after implementation and verification of modified operational procedures, HIFI redundant has meanwhile been successfully switched on again. See the paper by Teyssier et al in the proceedings of this conference[3]. Current work involves refinement of (autonomous) recovery procedures reducing the loss of observing time in case of future SEU's.

VII. Acknowledgement

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