Report on ASPOC onboard CLUSTER 1

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1 Scope

This document describes the failure which has occurred at the instrument ASPOC onboard spacecraft CLUSTER-1 and possible consequences on the scientific performance of the mission.

2 Instrument Overview

2.1 Scientific Objective

The primary objective of the investigation lies in the reduction of the electrostatic potential of the spacecraft with respect to the ambient plasma. Typical floating potentials of up to ≈50 V inside the magnetosphere obscure the measurements of the particle instruments at low energies due to the modifications in their energy and angular distribution which the particles experience in the potential well around the spacecraft. Also photo-electrons generated at the spacecraft surfaces are trapped by the potential and return to the electron sensors onboard, thereby superposing the electrons from the plasma.

2.2 Principle of Operation

The reduction of the positive potential of the spacecraft is achieved by the emission of positive ions with energies large enough that they can penetrate the potential well around the spacecraft and with currents which balance the high energy tail of the photo-electron current.

ASPOC utilises Liquid Metal Ion Sources (LMIS) with Indium as the source material. A solid needle, wetted by indium, is mounted in a heated reservoir with the same charge material. An ion beam forms when a potential of 5 to 10 kV, depending on the characteristics of the emitter, is applied between the needle and an extractor electrode.

2.3 Redundancy concept

The instrument consists of a single box, containing the processor unit, the main power supply, the heater supply, and the high voltage supplies (Figure 1). Four individual ion emitters are contained in one ion emitter "module" and are operated one at a time. The selection of the operational emitter is accomplished by heating this individual emitter. All emitters in one module have a common extraction and focusing lens arrangement and are powered by a dedicated high voltage cascade. The instrument carries two modules, mounted on top of the electronics box, so that in total eight emitters are available. Each emitter reservoir contains 250 mg of indium, which is sufficient for at least 4000 hours of operation at 10 µA per emitter. The total operating time requirement for the CLUSTER mission over two years at ≈50% coverage is 8,760 hours. Therefore 10,000 hours have been specified for ASPOC, which can be achieved by 2.5 emitters with nominal performance. The remaining emitters serve as back-up.

Redundancy is also given by the presence of two separate high voltage cascades. Whereas the digital processing unit and the low voltage side of the high voltage supply are not redundant, there are separate high voltage cascades including the secondary side of the transformer, and the current and voltage monitors for each module. The switching of high voltage between modules is done by a latching relay at the primary side.

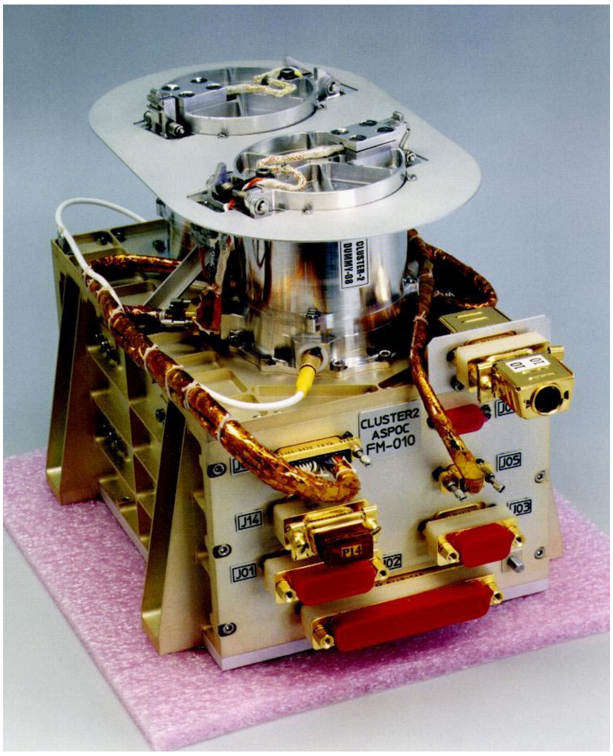

Figure 1. Instrument ASPOC FM-010

3 Event History

The payload of CLUSTER-1, launched on August 9th, 2000, contains the ASPOC unit FM-010.

The opening of the covers of the ion emitter modules, the initial turn-on of the processor, and the initial operation of the heater elements for the emitters took place on August 16th, 2000 between 04:30 UT and 05:40 UT. All parameters were nominal.

The initial turn-on of the high voltage and the initial operation of the ion emitters was scheduled for the night from 26th to 27th August (day 239-240). The instrument power had been turned on from 20:24 UT on day 239 until 01:16 UT on day 240.

The turn-on of the individual emitters started with module A. All emitters of this module were started successfully in the sequence (A2, A3, A4, A1) with ignition voltages of 7.3, 8.3, 7.4, and 7.0 kV, respectively. The operating voltages following the ignition were 7.5, 5.3, 7.3, and 6.7 kV, respectively.

For turning on the emitters of module B (serial number C2-04) the sequence (B1, B3, B4) was followed. The ignition voltages of B1 and B3 were 7.3 and 7.7 kV, respectively. Emitter B4 was expected to require somewhat higher voltage, since the ignition voltage during the final functional test on the ground was 8.7 kV. In flight operations the voltage increased to 9.6 kV without signatures of ignition. The housekeeping telemetry packet time stamped 00:53:28.51 UT, containing data acquired after 00:53:18.51 UT, showed the first anomaly:

The contents of this packet is shifted by 18 bytes, i.e. the first 18 bytes contain arbitrary values. The data starting with byte 18 repeat exactly the contents previous frame. Obviously the telemetry buffer in ASPOC was not updated between the two pollings, and in addition the buffer was not properly clocked out into spacecraft telemetry. The following frame, acquired after 00:53:28.51 UT, is again normal, except that the timer of the incoming sun reference pulse (SRP) does not follow the regular pattern consistent with one pulse per spin period, but is lower by ≈0.25 seconds. This indicates that the counter used to time-tag the incoming SRP started with a delay of about ≈0.25 seconds. This signature might be used to time the event exactly.

The status of the instrument immediately after the event was as follows.

- The bit indicating the presence of the high voltage disable connector was flipped, as if a safety connector were mounted.
- The high voltage monitor showed a value of 9(hex) = 0.35 kV, which is compatible with the value in the configuration that the safe connector is mounted and maximum high voltage is commanded.
- The analogue voltage generated by the processor unit, which controls the voltage output of the high voltage converter, was 4.95 V, indicating that the processor still commanded high voltage to the supply.
- The total current monitor of the high voltage chain showed zero current.
- The instrument did NOT autonomously change mode into standby, as it would have done in case watch-dog of the processor would have detected an anomalous operation.

After detection of this event in telemetry the instrument was commanded into standby mode.

Afterwards the functioning of the high voltage supplies was checked by commanding the voltage of 1 kV in Technical Mode, without heating of an emitter. The result was the same for both chains, A and B: Although the setting of the analogue voltage controlling the supply was at 0.5 V, equivalent to commanded 1 kV at the high voltage side, the actual output voltage of the high voltage cascade as indicated in the high voltage monitor, was 1(hex) or 40 V.

4 Analysis

4.1 Assessment

The relevant signatures of the event and the associated interpretation are as follows.

- Anomalous structure of one telemetry packet, but no reset or autonomous switching into standby mode by the processor; all analogue control voltages remain correct after the event; the processor continues to operate fully nominally.

The effect of the event, whether it was a discharge in the emitter module and/or in the high voltage supply, or some other failure, remained largely localised to low voltage side of the high voltage supplies.

- A wrong status of the high voltage disable connector is monitored.

During ground operations the disable connector short-circuits a line ("ARM") to ground, which is connected to +5V through a pull-up resistor of 100 kΩ. This line is fed in parallel to a Field-Programmable Gate Array (FPGA) of the Actel type, which forwards this information to the processor. In addition, this line is fed into a multiplexer of the type HCC4053B (manufacturer :SGS). This integrated circuit prepares the analogue output to the pulse width modulator which regulates the high voltage. The most important functions of this circuit are the switching between voltage controlled and current controlled operation of the supplies, and the comparison of the relevant measurement (i.e., the high voltage or the current monitor) with the analogue set value generated by a digital-to-analogue converter on the processor board.

The HCC4053B has 5 input signals:

- "ARM", the high voltage disable connector line
- "HVM", the output of the high voltage monitor
- "TCM", the output of the total current monitor
- "FBC", a status line indicating whether the HVM or the TCM signal shall be used for control
- "BCC", the set value for high voltage or total current (depending on the status of FBC)

The signature that the ARM signal is short-circuited to ground is as strong indication for a failure of the HCC4053B, which involves an internal short-circuit of its input.

The input lines HVM, TCM, FBC, and BCC, which are also monitored by the processor, show no signature of short-circuits: The values seen by the processor are at the expected levels. (The TCM line cannot be assessed in full since zero current is expected.)

This component receives input signals from the high voltage chain (the monitors). Although all lines have been secured by suppressor diodes, a transient voltage generated by a discharge on the high voltage may have propagated to this component.

The location of the discharge remains unknown. As the operation at 400 V after the event has shown, no permanent current leakage path has been formed. All signatures point at a minor event, which unfortunately hit this multiplexer.

4.2 Probability of Recovery

Due to mass and volume constraints the controller of the instrument (both the digital processor and the high voltage controller) could not be built in redundancy, and the multiplexer HCC4053B was necessarily non-redundant as a consequence of this design. The fact that the other four input lines of the failed component do no show signatures of short-circuit gave rise to some, albeit very faint, hope that some work-around might be possible to by-pass the erroneous "ARM" signal.

Detailed analysis, however, shows that the limitation of the high voltage by a LOW signal on the ARM line is hard-wired into the instrument. Any recovery would only be possible under the condition that the HCC4053B is revived. As one cannot know the extent of the damage to this component, some recovery due to aging or ionising radiation cannot in principle be fully excluded in case that the damage had been marginal. **However, in the most probable case, the failure must be considered to be permanent.**

5 Impact on the Scientific Mission

The failure to activate ASPOC on CLUSTER-1 leads to spacecraft potentials up to ≈50 V in the lobes of the magnetosphere. First measurements of the potential by the instrument EFW during the first weeks of the commissioning showed indeed peaks of the potential at ≈50 V in the lobes. On the other hand, the spacecraft potential expected and observed in regions with higher plasma density is well below this value. Pedersen ('Solar Wind and Magnetosphere Plasma Diagnostics by Spacecraft Electrostatic Potential Measurements', *Ann. Geophys.*, **13**(2), 118-129, 1995) has approximated earlier observations by an analytical expression. Applying this result to Cluster and assuming a thermal energy of the plasma electrons of 100 eV, we get spacecraft potential estimates of

N [cm^{-3}]	Vsc [V]
0.0001	71
0.001	54
0.01	38
0.1	22
1.0	9
10.0	4

A plot of spacecraft potential measurements over about one orbit (Fig. 2) confirms the expected variation of the spacecraft potential between ≈0 V in the plasmasphere near perigee, of ≈10 V in the plasmasheet, and higher values in the lobes. The orbits at this time of the year do not extend into the cusp, the magnetosheath or the solar wind, where typically higher plasma densities prevail (above or well above 1 cm^{-3}). In all these regions, all of which being of scientific importance for the mission, the uncontrolled spacecraft potential is expected to by below 9 V.

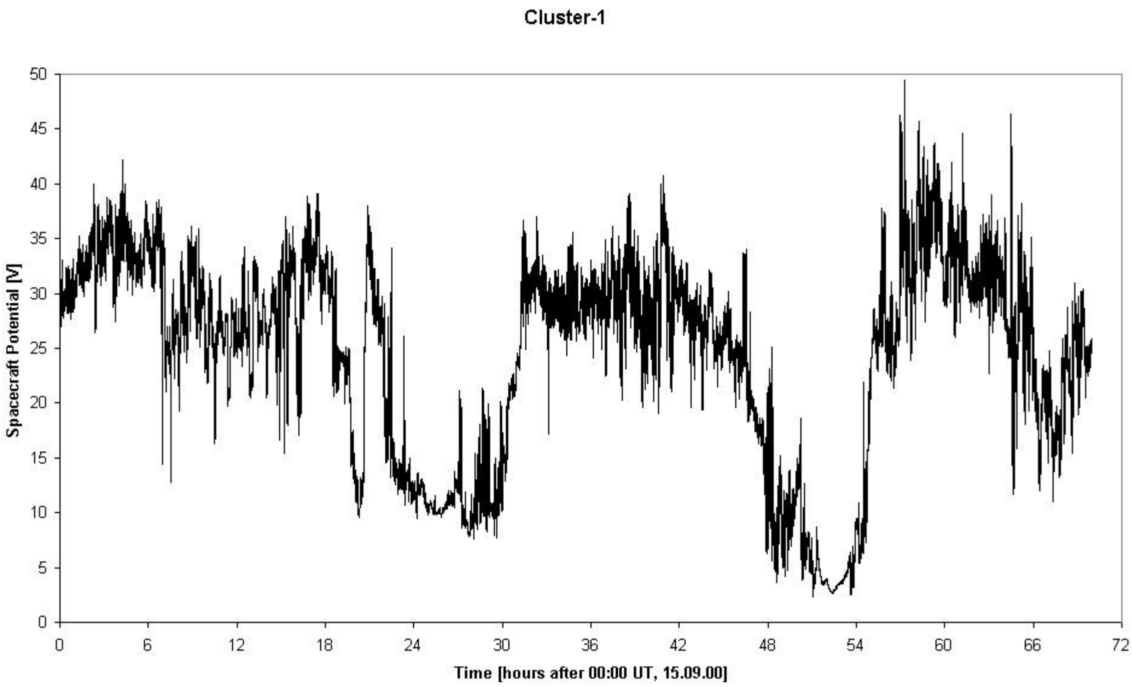

Figure 2. Typical variation of the spacecraft potential on a Cluster orbit in September, 2000.

Therefore the first conclusion is that the failure of ASPOC on CLUSTER-1 mainly affects measurements in the lobes of the magnetosphere. The measurements in the plasmasheet are much less affected, and for measurements in the magnetosheath, the cusp and the solar wind hardly any impact is expected.

Secondly, low spacecraft potentials serve to extend the energy range of particle instruments to lower energies. Onboard CLUSTER, the instruments PEACE and CIS gain most from active spacecraft potential control. In this context it should be mentioned that the four-spacecraft concept is not equally important for all types of instruments. Whereas the magnetometer and the wave experiments can measure vector quantities with high accuracy, the particle instruments may very often measure identical values on all spacecraft, depending on the scale length of the plasma components, also depending on energy. It is, however, fair to say that without ASPOC some results cannot be obtained, particularly for the low energy plasma.

As a third point, it must be mentioned that limitations of the data volume lead to the fact that the particle instruments cannot telemetre all the data they acquire. The instruments always have to make a compromises for the resolution in time, energy, angle, and species. Highest time resolution can be associated with a small energy band and/or a limited angular resolution.

One work-around for particle instruments in the absence of spacecraft potential control would clearly imply a concentration on higher energies, with maximum resolution in time and angle in the remaining energy band. Assuming that ASPOC on the other spacecraft will work, the particle instruments on these other spacecraft could concentrate on the lower energies.

6 Conclusion

The failure of ASPOC on CLUSTER-1 is due to a component which is central to the control of the high voltage and which probably has been destroyed by a discharge somewhere in the high voltage section (cascade, harness, emitter module).

The failure is likely to be irrecoverable as there is no possibility to by-pass the failing component by re-programming.

The scientific return of the instruments PEACE and CIS is affected. There is only negligible or no impact on other instruments.

The particle instruments can partially recover the lost capability to measure the low energy component in very tenuous plasma regions by concentrating on higher energies, by re-allocating data rates from low to high energy measurements. In several other regions covered by the mission, for example the solar wind, the cusp, the plasmasheet, the impact even on particle instruments is minor due to the low spacecraft potential in these regions.