Electrical Integration of the VenSpec Spectrometer Consortium: An Architecture Trade-off

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ABSTRACT

For ESA's EnVision Mission to Venus, a consortium of three spectrometers from across Europe has been formed to collaborate not only on the management and science aspects, but also on the technical implementation. One important technical goal of the VenSpec suite is to implement a clean, simple and robust interface to the spacecraft and to provide an abstraction layer between the channels and the spacecraft. This is achieved by implementing the Central Control Unit (CCU), which provides a harmonized power and data interface to the spacecraft and allows the channels to design for a simple tailored internal interface to the CCU. The CCU consists of two electrical subsystems, the Data Handling Unit (CCU DHU), developed by the Max Planck Institute for Solar System Research (MPS) in Göttingen and the Institute of Computer and Network Engineering (IDA) in Braunschweig and the Power Supply Unit (CCU PSU), developed by the Instituto de Astrofísica de Andalucía (IAA-CSIC) in Granada, the system responsibility being at the DLR Institute of Planetary Research (DLR-PF) in Berlin. Within this framework, an extended electrical architecture trade-off was performed in 2023 to optimize the system, guaranteeing the requested functionality and complying to requirements from all sides. As a result of the trade-off. a single power and data interface were found to be the most suitable and robust solution considering performance, reliability, Fault Detection Isolation and Recovery (FDIR) and Electromagnetic Compatibility (EMC) considerations as well as the complexity of the associated verification campaign. This paper demonstrates the options that were suggested by the different parties and justifies the final architecture, which has been chosen to achieve the best solution for the VenSpec suite.

Keywords: envision, venus, spectrometry, planetary science, data handling, power supply, control unit, electrical architecture

1. INTRODUCTION

ESA´s EnVision mission will determine the nature and current state of Venus' geological evolution and its relationship with the atmosphere, to understand how and why Venus and Earth evolved so differently. Located at the inner edge of the habitable zone, Venus may have once been habitable, with liquid water oceans, before developing the enormous greenhouse warming which renders it uninhabitable today, thus providing a natural laboratory for studying the evolution of habitability. Venus is geologically Earth's closest sibling: similar in size to the Earth, it has remained active to this day, unlike the much smaller Mars and Mercury. Venus is essential for understanding the links between planetary geophysical evolution and the habitability of terrestrial planets from our own Earth to terrestrial planets and exoplanets everywhere [1,2].

On-board the EnVision mission are three spectrometers (VenSpec-U, -H and -M), to investigate Venus' geology and atmosphere. VenSpec-U, an ultraviolet spectrometer (190-380 nm), will monitor highly variable minor sulfur species (mainly SO and SO2), the UV absorber and investigate the cloud tops, in a search for linking these variabilities with lower atmospheric and/or surface processes [3,4]. VenSpec-U is developed by the Laboratoire ATMosphères, Observations Spatiales (LATMOS). VenSpec-H is a high spectral resolution near-Infrared spectrometer. The main objective is to detect variations of CO, OCS, HF, HCl, SO2 and H2O abundances in the atmosphere, below and above the clouds, characterizing gas exchanges from the surface and within the atmosphere, searching for sources such as volcanic plumes [5,6]. VenSpec-H is developed by the Royal Belgian Institute for Space Aeronomy (BIRA). VenSpec-M is a push-broom multispectral imager optimized to map thermal emission from Venus' surface using six narrow bands ranging from 0.86 to 1.18 µm, and three bands at 1.195, 1.31, and 1.51 µm to study cloud microphysics and dynamics. This allows mapping of surface composition, by characterizing emissivity variations, as well as searching for thermal anomalies associated with volcanic activity [7,8]. VenSpec-M is developed by the German Aerospace Center Institute of Optical Sensor Systems (DLR-OS). In the following, the spectrometers will also be referred to as channels. They are electrically connected to the Central Control Unit (CCU) that provides the electrical interface to the spacecraft. Together they form the VenSpec suite. While the instruments are programmatically independent, each under their own PI, the DLR Institute of Planetary Research (DLR-PF) acts as a coordinator for the consortium and leads the collaborative effort of the science and engineering teams from all parties. Its main task is the coordination of all topics related to multiple subsystems of the suite including topics such as requirement flowdown, Fault Detection Isolation and Recovery (FDIR) mechanisms, Electromagnetic Compatibility (EMC) and electrical budgets.

The CCU consists of two electrical subsystems, the Data Handling Unit (CCU DHU), developed by the Max Planck Institute for Solar System Research (MPS) in Göttingen and the Institute of Computer and Network Engineering (IDA) in Braunschweig and the Power Supply Unit (CCU PSU), developed by the Instituto de Astrofísica de Andalucía (IAA-CSIC) in Granada, the system responsibility being at the DLR Institute of Planetary Research (DLR-PF) in Berlin.

The technical goal of the VenSpec suite is to implement a clean, simple and robust interface to the spacecraft and to provide an abstraction layer between the channels and the spacecraft. In order to find the best solution for the spacecraft and the consortium of the three spectrometers, an extended electrical architecture trade-off was performed in Q2&Q3 2023 in phase B1 and during the transition of ESA from the study team to the project team. For the trade-off, it was decided to consider a variety of options, ranging from no CCU to separate data handling units that could be integrated directly into the mechanical structures of the individual spectrometers. At the time of the trade-off, the spectrometers already had a preliminary design, which was considered, when deciding on the best solution. Furthermore, the proposal for the VenSpec suite, and therefore the funding, already included some type of CCU, influencing some design decisions. It is also worth noting that the spectrometers were in the phase of their own System Requirement Review (SRR) during that time frame and therefore needed to finalize their preliminary designs.

The overall goal of the trade-off was to achieve the most suitable and robust solution considering technical as well as programmatic criteria. Further descriptions of the programmatic boundary conditions of the consortium are described in [9].

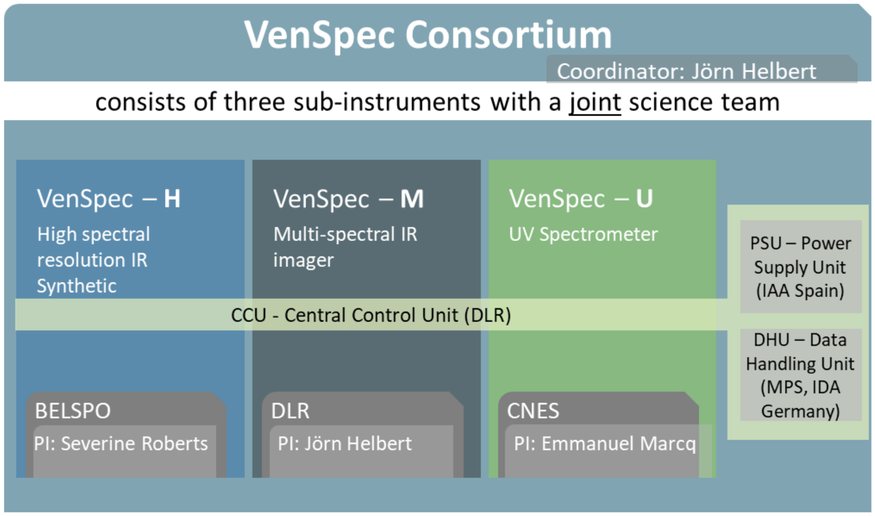

Figure 1. Venspec consortium

2. TRADE-OFF CRITERIA

To compare different design solutions, the trade-off criteria need to be selected. Furthermore, a weighting of all the criteria for a particular design decision is also carried out in the relevant sections.

The following trade-off criteria are selected:
Electrical interface: This criterion is technical and includes aspects such as interface complexity, e.g. number of interfaces; and data budget.
Complexity: This criterion is technical and includes design and software complexity.
Verification: This criterion is technical, since it includes the needed effort that results from the size of the requirements set.
Parallelized Testing: This criterion is programmatic, since it includes schedule and schedule risks as well as needed resources.
Mass: This criterion is technical and includes the needed mass.
Volume: This criterion is technical and includes the needed volume.
Power: This criterion is technical and includes the needed power.
Electromagnetic Compatibility (EMC): This criterion is technical and includes EMC aspects such as radiated emission.
Fault Detection Isolation and Recovery (FDIR): This criterion is technical and includes FDIR aspects such as the implementation of an intermediate FDIR layer.
Costs: This criterion is programmatic and includes funding aspects and hardware costs.

Only options that are high-TRL and already have heritage from other missions such as JANUS DHU and GALA DPU were selected for the trade-off.

3. IMPLEMENTATION OF A CENTRAL CONTROL UNIT (CCU)

Based on the fact that the baseline concept included a CCU, the question arises as to what advantages and disadvantages a solution with a CCU has compared to a solution without a CCU.
Considering that the funding for a CCU was independent from the funding of the channels and it was already allocated, the omission of the CCU would not lead to a reallocation of the funds to the channels, giving no advantage regarding the costs. On the contrary, it allows for functionalities and verification to be outsourced from the spectrometers to the CCU.

Implementing a CCU for all channels allows a collaborative approach, leading to a common vision for science operation, planning and analysis as well as sharing of data and joint publications. Competition for data and power budgets towards the spacecraft prime can be reduced by a mutually agreed operations plan. In order to reach a collaborative approach, resources are needed to manage and align all concepts regarding operations as well as common design topics, such as EMC, FDIR and software.

With the implementation of a CCU, the spectrometers have no direct electrical interface to the spacecraft, which allows a simpler and more flexible interface between the channels and the CCU. The complexity of the interface requirements and the verification effort on the spectrometer side can thereby be reduced. On the other hand, adding a CCU between the spectrometers and the spacecraft comes with extra complexity of additional technical and formal interfaces.

Since ESA considers the CCU and the channels as one instrument, requirements need to be flowed down to the channels, which leads to a significant additional work for the VenSpec system engineer. On the other hand, this setup allows a tailoring of the interface to the channels and achieve some degree of independence from the spacecraft interface. This freedom extends from physical and SW implementation to requirements on documentation and verification that can be tailored specifically to the needs of this type of instrument class.

Taking all mentioned aspects into account, the implementation of the CCU for the VenSpec suite was jointly agreed by the VenSpec consortium and ESA. This allows the extension of the collaborative effort of VenSpec from a joint science team to collaborative engineering, thereby levering synergies and encouraging concurrent development.

Since three spectrometers are dependent on the CCU, the decision was made early on in the trade-off to design it with cold redundancy to ensure the design is single-point-failure free. This means that no channel will be lost for the mission even if on side of the CCU fails.

4. IMPLEMENTATION OF A DATA HANDLING UNIT

For the implementation of the CCU different concepts are possible. The CCU consists of some type of power supply unit and if necessary a data handling unit. The need of a DHU apart from the internal data handling already foreseen inside some of the spectrometers results from the downlink budget of the EnVision mission. The mission is downlink-constrained due to the high data volume of e.g. the VenSAR synthetic aperture radar. It requires a compression of at least 1.4 to ensure compliance to the system-level downlink constraints while maintaining the spectroscopic accuracy and coverage required to fulfill the VenSpec science goals. Not all channels are able to provide such a compression with their current design constraints, making an implementation of an additional CCU DHU preferable.

Furthermore, the communication interface to the spacecraft will be handled by the CCU, allowing command translation and therefore tailoring and early freezing of the channel telecommand interface. This was one of the advantages mentioned in the section above for the implementation of a CCU at all.

Whether the implementation of the compression would be done inside the CCU or the spectrometers, the mass and power would increase either way. So, the downlink constraint being a stronger driver on system level than the small additional increase in mass incurred through the CCU, the additional data handling functionality was considered highly beneficial.

Table 1. Results for the implementation of a data handling unit.

Criteria	Weighting
Electrical interface budget (data)	+2
Mass	-1
Power	-1
Verification	+2
Sum	+2

In conclusion, it can be said that the implementation of a CCU DHU is the best solution for the given demands and conditions.

4.1 Architecture concepts for a Central Control Unit Data Handling Unit (CCU DHU)

For implementing a DHU in the CCU two possibilities are to be considered. On one hand, it is possible to have a dedicated DHU for each channel, leading to a 3-DHU version. On the other hand, a common DHU for all spectrometers can be realized, having a 1-DHU version.

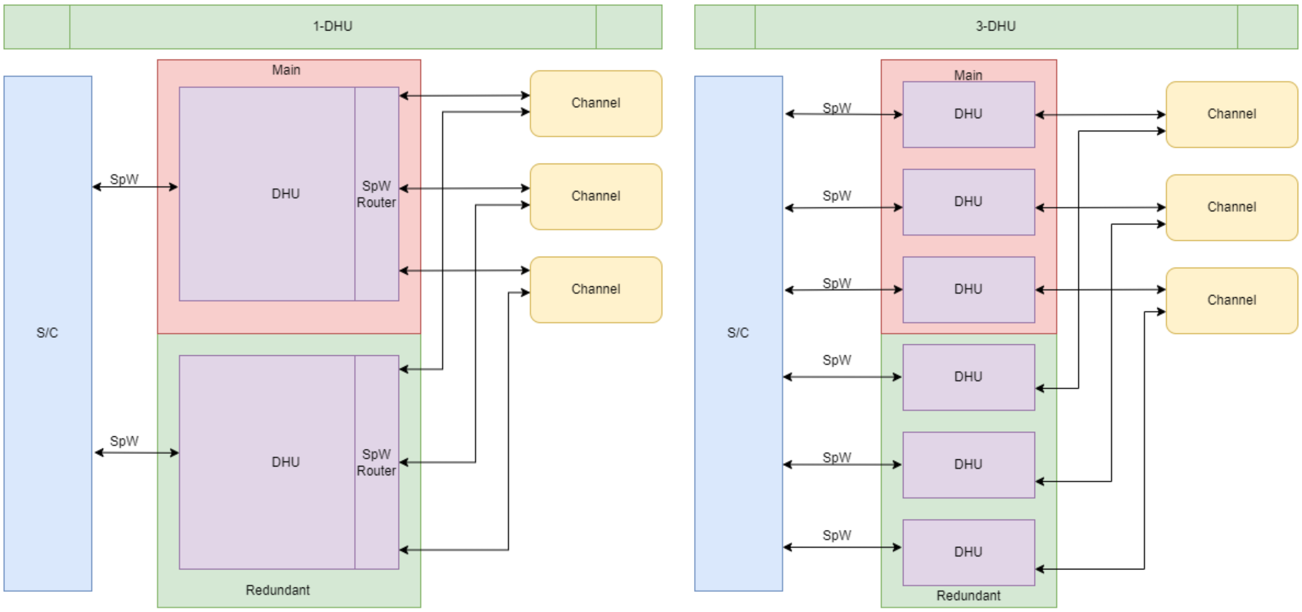

Figure 2. Architecture concepts for one and three data handling units.

In the 1-DHU version, only a single SpaceWire connection to the spacecraft (S/C) would be needed. The DHU would serve the function of multiplexing the three individual data streams into one SpaceWire connection to the Solid State Mass Memory (SSMM) and On-Board Computer (OBC) of the spacecraft. The spectrometers would retain individual Application Process IDentifiers (APIDs) and the commands would still be directly addressed to the channels. The 3-DHU version would contain three SpaceWire connections between the CCU and the S/C SSMM and OBC. Each channel would be connected to a DHU that serves only that specific spectrometer and is not connected to the other two. Each DHU as well as each channel would have an individual APID. Having three DHUs would mean that the satellite would have to provide three communication interfaces to the CCU, resulting in a more complex interface for the spacecraft.

When realizing the 1-DHU option, the DHU software (SW) needs to be able to handle all channels simultaneously, making the software more complex compared to the 3-DHU option. The verification procedure of this common SW will also be more complex due to the increase of complexity of the software itself. On the other hand, the overall verification effort and documentation is expected to be less for the 1-DHU version, since only one software needs to be verified instead of three individual software, even if parts of the software are the same for the three spectrometers. This highly influences needed resources and has the largest impact on the design decision.

For the spacecraft, the VenSpec suite is seen as one instrument with one electrical interface, which makes verification and testing on suite level necessary. Having only one DHU for all spectrometers results in a relatively late verification and testing campaign of the whole suite, since the final setup can only be tested after the verification of each individual channel. Compared to that, the 3-DHU version enables a mostly parallelized verification approach, since all spectrometers can verify their performance with their individual DHUs and are not dependent on each other. Only some tests, such as EMC still need to be done on suite level.

The obvious advantages of the 1-DHU version compared to the 3-DHU version are the lower hardware (HW) costs, since fewer components are required and the mass and power budget are lower. As already mentioned, these factors are not critical and have therefore less impact on the design decision.

Table 2. Comparison between the implementation of one or three data handling units.

Criteria	1-DHU	3-DHU
Electrical interface complexity (No. of SpaceWire interfaces)	+1	-1
Software complexity	-1	+1
Software verification	+2	-2
Parallelized testing	-1	+1
Hardware costs	+1	-1
Power	+1	-1
Mass	+1	-1
Sum	+4	-4

Mainly due to the high demand on verification effort for the 3-DHU version it was decided to implement one common DHU for all channels.

5. IMPLEMENTATION OF A POWER SUPPLY UNIT

At the time of the trade-off it was already decided, that each channel has its own power supply inside their respective spectrometer. Therefore, the CCU PSU competences lie with the power supply for the CCU DHU and possibly the switching of the spectrometers.

Different implementations for the required functionalities are possible, leading from no switches for the spectrometers inside the CCU PSU to power switches and return path switches inside the CCU PSU. The option for return path switches needs to be discussed due to the fact, that the spectrometers have no redundancy, but the CCU does. Not implementing return path switches could lead to potential EMC problems, because of high return currents through the redundant return path. The resulting radiated emission could exceed EnVision's very stringent Radiated Emission (RE) limits, required due to the implemented Subsurface Radar Sounder (SRS).

5.1 Option 1: No power switches inside the Central Control Unit (CCU)

In this option the CCU PSU has no switches implemented. It is the most minimalist version and means that the spacecraft directly controls the power interface of the spectrometers via the spacecraft latching current limiters (LCLs). It reduces the complexity of the CCU PSU and no return path switches need to be foreseen, since the spacecraft would be responsible.

When choosing this option, the channels would have a direct electrical interface to the spacecraft that needs to be verified. The documentation and verification effort will therefore be higher than for an internal interface.

Since no power interface to the CCU is implemented, the CCU is not able to switch the channels independently on and off. Therefore, any failure condition that the channels cannot resolve on their own would have to be handled by the spacecraft. When realizing this design, the CCU DHU has no means to know if a channel is off or on and it would be necessary for the spacecraft to report the state of the channels to the CCU DHU. More power interfaces to the spacecraft would be necessary, since each spectrometer and the CCU DHU need one.

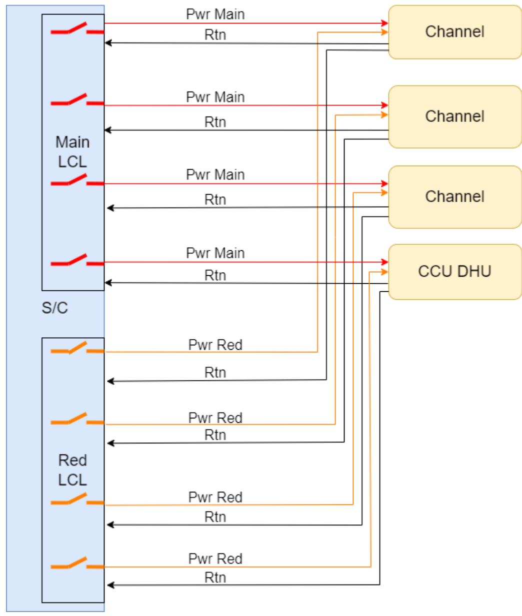

Figure 3. Option 1 for the implementation of a power supply unit.

5.2 Option 2: Power switches inside the Central Control Unit (CCU)

Option 2 foresees switches inside the CCU PSU that allow the CCU to switch on and off the channels independently from the S/C. That reduces the number of power interfaces to the S/C to only one per CCU (Main + Redundant) and allows the suite to implement internal FDIR mechanisms as an additional layer. With that it is possible to react on telemetry and requests from the spectrometers independently from the spacecraft and allow recovery mechanisms, such as automatic reboot of the channels. This option does not foresee return path switches, which saves volume, mass and power dissipation, but might lead to EMC problems, such as additional emissions.

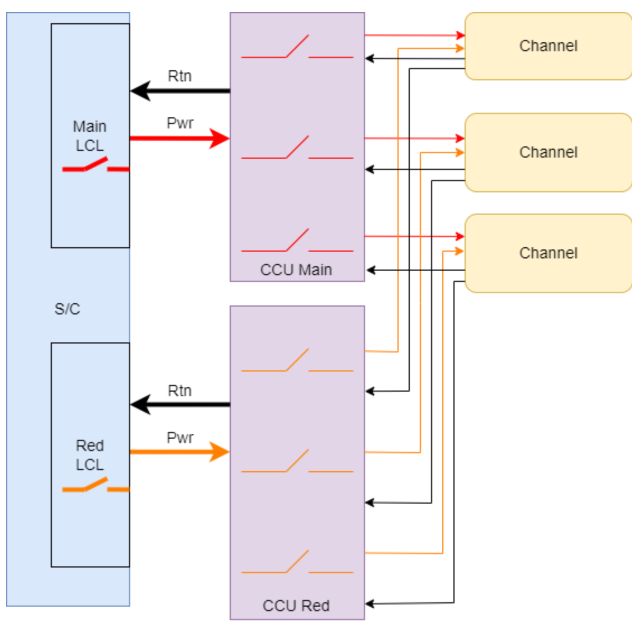

Figure 4. Option 2 for the implementation of a power supply unit.

5.3 Option 3: Return path switches inside the Central Control Unit (CCU)

The difference between option 3 and option 2 is that return path switches are foreseen inside the CCU to deal with the potential EMC problems. That leads to additional components necessary inside the CCU PSU. As a result, the CCU PSU would occupy a larger volume, have higher mass and a higher power dissipation.

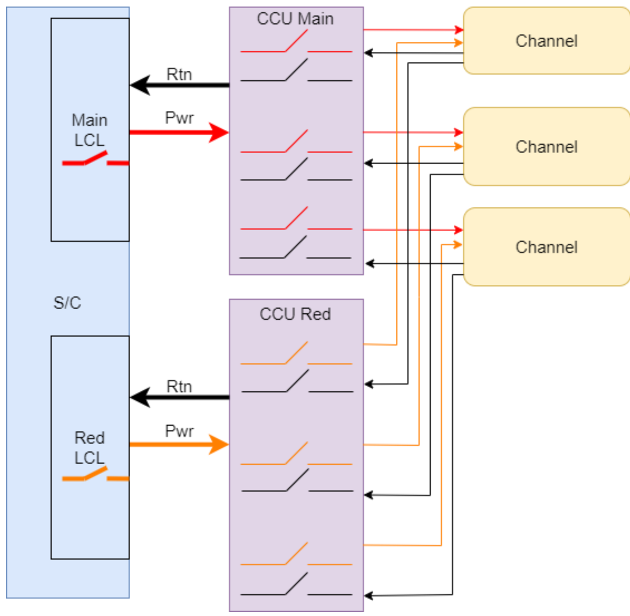

Figure 5. Option 3 for the implementation of a power supply unit.

5.4 Option 4: Return path switches inside the channels

The difference between option 4 and option 3 is the position of the return switches. Here, the return switches are placed inside the spectrometers. This would increase the space needed for the channel PSU with a higher power dissipation. The responsibility for the additional components for the return switches would lie with the spectrometers.

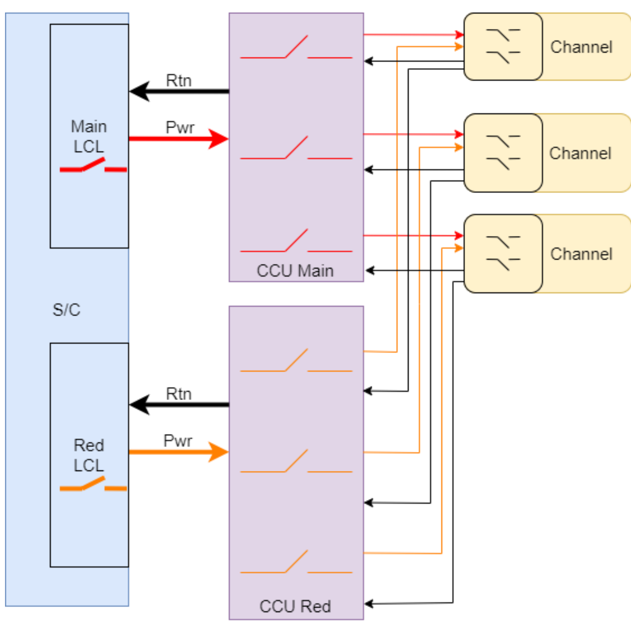

Figure 6. Option 4 for the implementation of a power supply unit.

5.5 Option 5: Switching via individual LCLs and DCDC converters

Option 5 is a combination of option 1 and option 2. The spectrometer power interface has a direct connection to the spacecraft and in addition extra switches are implemented inside the channel PSU. This way, the CCU is able to switch the channel on and off independently from the spacecraft. That allows the VenSpec suite to have an intermediate FDIR layer.

Also, no return switches are necessary for that solution as the return current will need to be controlled by the spacecraft. The drawbacks of this option are the direct power interface to the spacecraft and the resulting need for more resources due to the higher verification and documentation effort. Furthermore, it is necessary to implement additional circuits inside the spectrometer power supplies to allow the DHU to switch and observe the status of the channel PSUs.

The number of power interfaces needed is also increased to the maximum of four. It is also worth mentioning that the DHU can observe the status of the channel PSU and switch it, but still depends on the communication with the spacecraft in case that one of the channels is not enabled when it should be or vice versa. In options 2, 3 & 4 with only one power interface towards the spacecraft, tripping the LCL of the spacecraft will turn off the whole suite. This option as well as option 1 allows for only latching one channel or DHU.

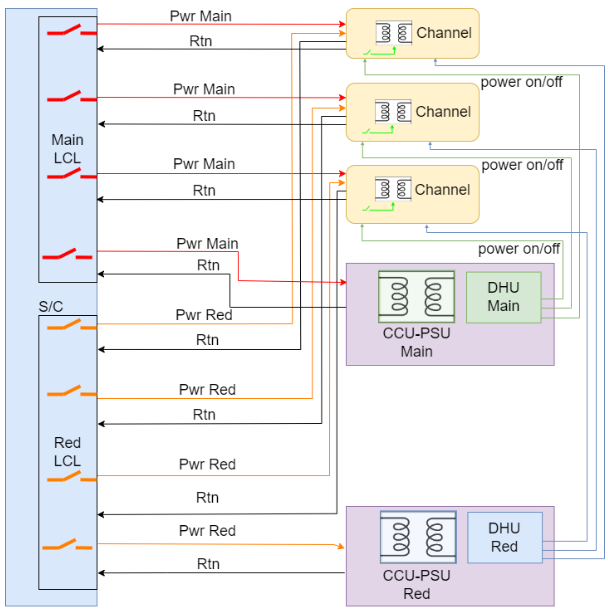

Figure 7. Option 5 for the implementation of a power supply unit.

5.6 Comparison of the options

The different options were compared and a trade-off can be seen in the following table.

Table 3. Comparison of the options for the implementation of a power supply unit.

Criteria	Option 1	Option 2	Option 3	Option 4	Option 5
Electrical interface complexity (No. of spacecraft interfaces)	-1	+1	+1	+1	-1
EMC (return path switches)	+1	-1	0	0	+1
Intermediate FDIR layer (switching of channels by the CCU)	-1	+1	+1	+1	+1
Verification	-1	+1	+1	+1	-1
Design complexity	+1	0	0	0	-1
Volume	+1	0	-1	-1	-1
Sum	0	+2	+2	+2	-2

Options 2, 3 and 4 are all suitable options for CCU PSU design. Since it is assumed that return path switches improve the EMC performance, options 3 and 4 are preferred. Furthermore, it is advantageous to include them in the early stage of the design as a risk-mitigation effort, since the magnitude of additional emissions cannot be quantified, instead of having to add them at a later stage, when problems may occur.

Options 3 and 4 are equal and the best options. The only difference between the two options is the position of the return path switches. Option 4 was chosen for the VenSpec suite because the volume constrains for the CCU were tighter and so it was easier to implement the return path switches inside the spectrometers.

6. CONCLUSION

During Phase B1, a full trade-off was performed that considered engineering as well as programmatic concerns of all stakeholders to determine the best solution for implementation. It was decided to have a full redundant CCU with an integrated 1-DHU option and power switches. The return path switches will be placed inside the spectrometers.

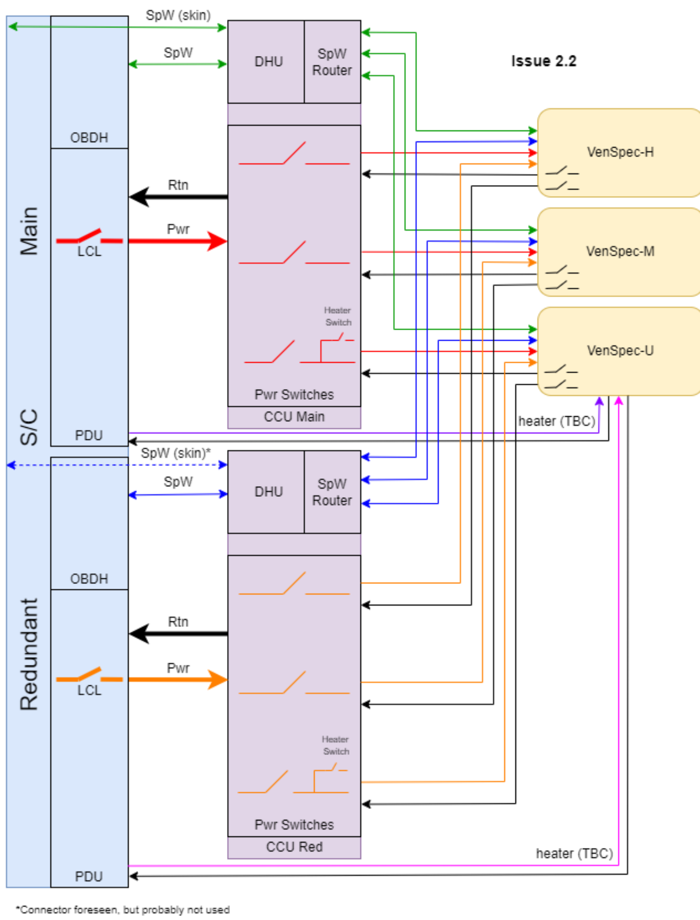

Figure 8. Electrical architecture of the VenSpec suite

The chosen solution reflects the collaborative spirit of VenSpec, encouraging and ensuring close collaboration of VenSpec-H, VenSpec-M and VenSpec-U throughout all phases of the mission.

7. LESSONS LEARNED

Although the project is still at the beginning, some lessons could already be derived.

The basis for the successful implementation of a consortium lies in the cooperation between the individual partners. Without a shared vision, this type of structure will not be successful, since all partners are equal. If such a cooperation can be accomplished, some advantages especially for the spectrometers can be achieved.

With a consortium of three spectrometers, requests towards ESA carry more weight, especially since the spectrometers are not the main payloads.

Since ESA views the VenSpec suite as one instrument, only one electrical interface needs to be verified to the spacecraft. The interface requirement set can be flowed down in a harmonized and tailored manner for the individual channels and solutions can be discussed in the consortium. Analysis can focus on those topics that are most pressing for spectrometers in particular. Similarly, due to the single interface to the spacecraft, a tailoring of the commanding interface to the channels is achieved in addition to offloading some amount of software verification effort from the channels to the CCU team. The time saved can be used for further development of the spectrometer itself. Budgets for power and data can be adapted, depending on the needs, since only an overall budget is specified. Tailored and common engineering solutions as well as harmonized engineering documentation will hopefully lead to a more efficient implantation phase.

One challenge for a shared requirement set lies in the flowdown of stringent requirements such as EMC, since the instrument limits apply. These limits then need to be distributed to the CCU and the channels, resulting in an even stricter sub-set of requirements.

Furthermore, the effort for the flowdown is not to be neglected and needs to be done in a proper way. This takes a lot of time for the CCU system engineer, especially at the beginning of the project.

Verifying all internal interfaces might require less effort on spectrometer side, but increases the effort on CCU side.

Looking back on this specific project, the trade-off was done at a relatively late stage, since the spectrometers already had a preliminary design, eliminating some design solutions, and were being right in the middle of their respective SRR.

The coordination of the consortium is rather complex and the success of this structure will become visible only after the completion of the project.

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