The VenSpec Suite Organization: Collaborative development from instrument proposal to scientific analysis

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ABSTRACT

VenSpec is an instrument-suite composed of three spectrometers sharing a central control unit. Tied together by the common goal of exploring the different layers of Venus from the surface to the upper atmosphere in a holistic manner, three instrument lead scientists from Germany (DLR), France (LATMOS) and Belgium (BIRA-IASB) have joined forces. From the outset of the phase A study a collaborative work environment has been put in place to enable synergistic scientific planning and development work from the initial conceptual design throughout the actual instrument development and leading up to the operations and analysis of scientific returns. This paper addresses the challenges the consortium has faced in the process of guiding geographically, financially and institutionally separated projects towards a common goal with as little organizational overhead to the teams as possible. In the case of VenSpec, the scientific aspiration of working together via a common science team was set down at the beginning of the project: the consortium was consolidated by assuring each party full access to all scientific data produced by any instrument and also by connecting them physically to a common central control unit. This enables the consortium to act as a single entity towards the European Space Agency as well as the prime industrial contractor when beneficial while giving each party the freedom to act independently of each other for those aspects of scientific planning or technical development in which harmonization is not required. This paper lays out how the VenSpec consortium is organized and explains how close collaboration and the leveraging of synergies can be balanced with independent activities and individual and tailored strategies.

Keywords: remote Sensing, scientific instruments, collaborative development, synergistic research, instrument consortium design, venus atmosphere, Spectrometers, atmospheric studies

1. A MISSION BASED ON PAST LESSONS LEARNED

When it is time to propose a new scientific mission, what is the best way to ensure as much scientific return as possible? Technology drives the data that can be generated and scientific know-how enables the generation of new information and knowledge, but this process can be hampered by the way scientific communities are organized. Rivalries, conflicting interests and competition for resources between teams can prevent sharing of data or collaborative work. The VenSpec consortium is a construction based on lessons learned in previous scientific missions and strives to provide a structure to guide an extensive scientific team spread over numerous institutions over a large part of the world towards a common goal. It is based on the philosophy that incentives and the framework for collaborative work are essential to provide a research environment that benefits all parts of the community. Planetary phenomena are inherently linked, which makes it essential to enable collaboration across national and institutional boundaries, to share data and know-how freely while

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preserving intellectual property. VenSpec has been established already at the earliest stage of the mission proposal and a joint science team is in place to guide the project until the very end of the mission, leveraging the synergies that will enable the profound understanding of the planetary neighbor that the scientific community seeks.

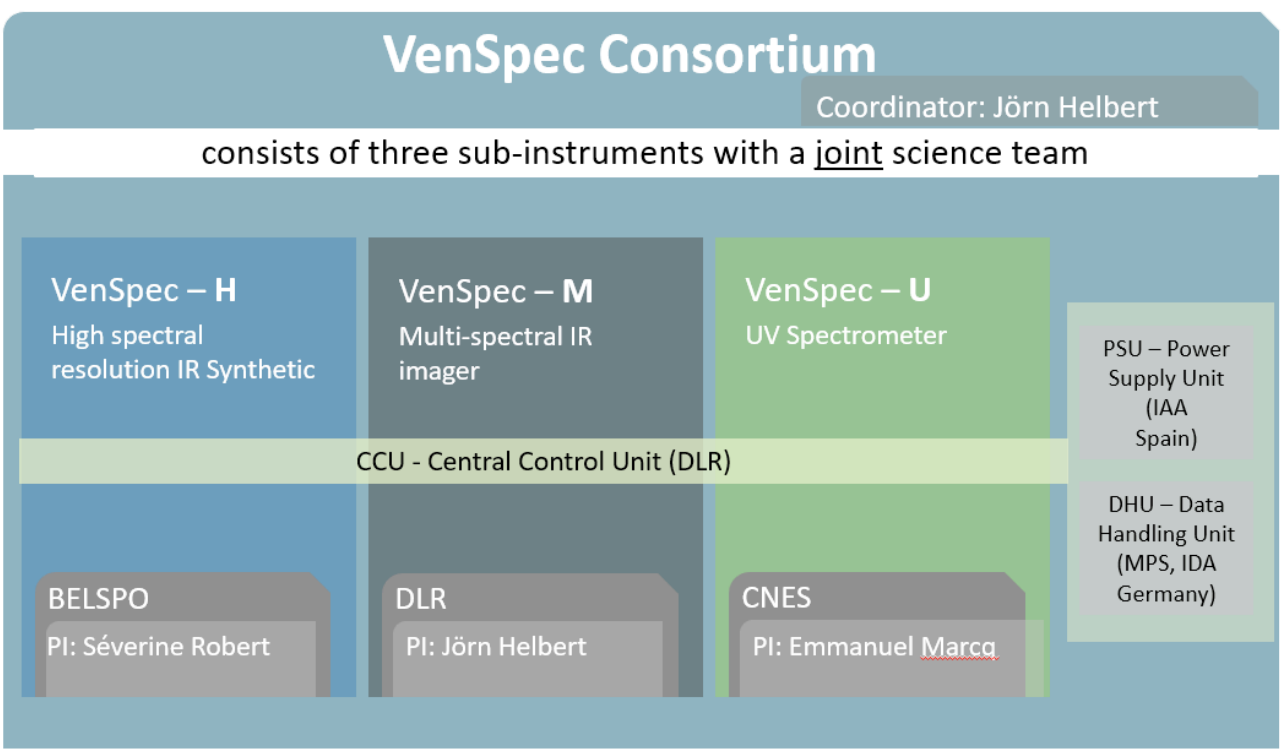
2. INTRODUCTION AND CONTEX

3.1. The EnVision Mission

EnVision is an ESA mission that will send an orbiter to Venus in the 2030s to understand its geological and atmospheric evolution to gain insight into why Venus and Earth have developed so differently. Venus might have been habitable at some point in time, and understanding the subsequent runaway greenhouse warming that has brought about its current state will provide insights into the planetary processes that enable or destroy the conditions for life. The mission will provide insights into the different evolution of Venus and Earth, that led to two geological siblings with similar starting conditions evolving to the states we know today.

3.2. VenSpec

Within the EnVision Mission, the VenSpec spectrometer suite will gather spectroscopic data from UV to IR. VenSpec will collect a data set from the surface to the upper layers of the atmosphere. It will be able to map the surface mineralogy and measure tropospheric and mesospheric gases. In addition, it will perform a comprehensive search for volcanic activity by targeting atmospheric signatures, thermal signatures and compositional signatures. This approach will enable the study of the coupled systems of surface and atmosphere on Venus with three complementary instruments. In combination, VenSpec will provide unprecedented insights into the current state of Venus and its past evolution. **VenSpec-U**, an ultraviolet spectrometer (190-380 nm), will monitor highly variable minor sulphur species (mainly SO and SO_2), the UV absorber and investigate the cloud tops, in a search for linking these variabilities with lower atmospheric and/or surface processes. **VenSpec-H** is a high spectral resolution near-Infrared spectrometer. The main objective is to detect variations of CO, OCS, HF, HCl, SO_2 and H_2O abundances in the atmosphere, below and above the clouds, characterising gas exchanges from the surface and within the atmosphere, searching for sources such as volcanic plumes. **VenSpec-M** is a pushbroom multispectral imager optimised 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 characterising emissivity variations, as well as searching for thermal anomalies associated with volcanic activity.
The three spectrometers (VenSpec-U, VenSpec-H and VenSpec-M) are complemented by the central control unit (CCU) which is a unit that functions as the sole electrical interface of the VenSpec instruments towards the spacecraft.



4. PARTICIPATING INSTITUTIONS

4.1. Instruments

LATMOS

The Laboratoire ATMosphères, Observations Spatiales (LATMOS) based in Guyancourt as well as in Paris is a French research laboratory specialized in the study of physical and/or chemical processes governing terrestrial and planetary atmospheres and their interfaces with the surface, the ocean, and the interplanetary medium. It has developed a strong instrumental expertise, constructing innovative instruments deployed from the ground, into Earth orbit or to other bodies in the solar system (e.g. Mercury, Venus, Mars, Titan). Numerical atmosphere models are also developed and used to interpret various observations. LATMOS provides the VenSpec-U instrument which will monitor sulphured minor species (mainly SO and SO_2) and the as yet unknown UV absorber in Venusian upper clouds and just above. It will therefore complement the two other channels by investigating how the upper atmosphere interacts with the lower atmosphere, and especially characterize to which extent outgassing processes such as volcanic plumes are able to disturb the atmosphere through the thick Venusian clouds.

BIRA-IASB

The Royal Belgian Institute for Space Aeronomy in Brussels is a research institute of the Belgian federal government specialized in space aeronomy, which is the physics and chemistry of the atmosphere of the Earth and other planets. VenSpec-H will be dedicated to high spectral resolution measurements in the atmosphere of Venus in the near-infrared wavelength range, both at its day side and night side. The main objective of the VenSpec- H instrument is to detect and quantify species related to volcanism in both the troposphere and the mesosphere, to enable characterization of volcanic plumes and other sources of gas exchange with the surface of Venus. VenSpec-H complements VenSAR and VenSpec-M surface observations, SRS subsurface observations and VenSpec-U observations in the upper cloud layer.

DLR-OS

The DLR institute for Optical Sensor Systems in Berlin is active in the domains of developing sensor systems in the UV, visible, infrared and Terahertz-range. The applications span a wide gamut from earth observation, robotics, planetary research, transport and security. VenSpec-M will provide near-global compositional data on rock types, weathering, and crustal evolution by mapping the Venus surface in five atmospheric windows. VenSpec-M will monitor for H_2O abundance variations close to the surface complementing VenSpec-H observations. In combination with the observations provided by the identical VEM instrument on the NASA VERITAS mission VenSpec-M will provide more than a decade of monitoring for volcanic activity, as well as search for surface changes.

4.2. CCU and Consortium Lead

The CCU is being developed under the responsibility of DLR with significant hardware contributions from MPS, IAA and IDA. The Mauà Institute of Technology will develop the EGSE used to enable efficient interface verification.

DLR-PF

The DLR Institute of Planetary Research in Berlin has developed numerous scientific instruments for the science and exploration programs of ESA, NASA and JAXA and provides infrastructure for this purpose. It combines scientific and technical expertise: DLR-PF has lead numerous prestigious scientific planetary research missions, from the initial phase of the scientific concept, via instrument design and realization, to instrument operation and scientific data processing and analysis. The main focus in terms of instrumentation are cameras, radiometers, laser altimeters and spectrometers. In addition, laboratory analysis of surfaces under extreme conditions and extraterrestrial samples are one of the foundations of the institute.

MPS (Max Planck Institute for Solar System Research) & IDA (Institute of Computer and Network Engineering)

The Max Plack Institute for Solar System Research aims to understand the processes in all the bodies in our solar system, from planets to smaller bodies like asteroids and comets using models and simulations but also by developing dedicated instrumentation for interplanetary missions. Space hardware from the Max Planck Institute for Solar System Research is currently on its way to Mercury and Jupiter, can be found on the surface of Mars, and in recent years has visited Venus, Saturn, comets, and asteroids. The scientific work of the Planetary Sciences Department in particular is to

understand the conditions under which these very different bodies once originated, how they evolved in the early phase of their formation, and what characteristics distinguish them today.
The Max Planck Institute contributes the Data Handling Unit (DHU) for the Central Control Unit in collaboration with IDA.

IDA
The Institute of Computer and Network Engineering in Braunschweig (Germany) is an institute of Technische Universität Braunschweig (TUBS). IDA actively contributes to the enormous progress in efficient, dependable and safe computers and network systems. A special expertise of IDA is the design of dedicated data processing units (DPUs) for space including high performance processing. Successful implementations were e.g. camera DPUs for Venus Express VMC, DAWN Framing camera, and JANUS instrument on the Juice mission. Recently, dynamic FPGA reconfiguration as well as in-orbit FPGA firmware update was successfully demonstrated in orbit for the Solar Orbiter PHI instrument DPU. Furthermore, IDA has developed a universal platform for high performance on-board data processing on basis of modern FPGA devices.

IAA-CSIC
The Institute of Astrophysics of Andalucía is a research institute with a broad scientific scope that spans the entire gamut of space research from astrophysics to solar system research. In addition to scientific activities, the institute is a major and well-reputed participant in many ESA missions, providing technical expertise and development of instrument subsystems and acting as an interface to the Spanish Space Industry. Among other things, IAA has significant know-how in the analogue and digital fields, digital signal processing (hardware and software) as well as design & development of circuits, power electronics, and PCBs. Cassini-Huygens (NASA-ESA-ASI), Rosetta (ESA) and JUICE (ESA) are only three of the missions that have had significant contributions from IAA.

IMT Mauà Institute of Technology
Instituto Mauà de Tecnologia (IMT) is a private, non-profit organization that offers courses as well as research programs in multiple areas of knowledge. Some of the major areas of the IMT are engineering, computer science and design. IMT is a member of the PLATO consortium for which it supplied the SimuCAM to enable interface verification. Building on this previous collaboration, IMT will contribute instrument simulators that will facilitate the verification campaign of the VenSpec suite by developing an EGSE.

5. THE VENSPEC IDEA IN PRACTICE

The entire idea of the VenSpec Consortium is based on the common vision of a joint science team. The consortium binds the three Instrument Lead Scientists (ILS) and their teams together to encourage joint decision-making, share information, implement common approaches and publish together and to do so in an efficient and timely manner to have the entire suite science-ready at launch.
When it comes to instrument contributions, there is power in size. In addition to VenSpec, the EnVision mission will host a synthetic aperture radar (VenSAR), a subsurface sounder (SRS) and a radio science experiment (RSE). A spectrometer is a small instrument compared to a radar in terms of physical size, funding and in the way it drives overall spacecraft design and resources and thereby attention. While equally important to the overall mission goal of understanding Venus, the concerns of smaller players risk being drowned out as time runs short and problems multiply. Therefore, joining ranks between instruments that are small and similar and acting towards ESA as a common team is an approach that is attractive to both sides. This enables Venspec to coordinate responses to questions, prioritize concerns towards ESA (and likewise ensure problems of the instruments are dealt with in equal measure), harmonize terminology to prevent confusion and misunderstanding, merge documentation to ensure efficient and equal information sharing to ESA and the spacecraft, agree on a sensible distribution of resources and share know-how on problems that apply to instruments equally. This arrangement enables shifting a part of the payload management that would typically be performed by ESA to DLR who is uniquely equipped to offer more targeted guidance for the collaboration of the three spectrometers due to its longstanding expertise in this particular field than a payload manager at ESA whose work has a broader scope and covers a wide range of instruments could provide.

6. BOUNDARY CONDITIONS

The ideal consortium does not exist. Institutions have political and financial boundary constraints, know-how is not evenly distributed and interests do not always align. Given the reality of the boundary conditions that the individual institutions face, VenSpec strives to create the most fitting structure that tries to benefit all stakeholders including ESA, national space agencies as well as the spacecraft contractor while taking into account their respective constraints and concerns. This section gives an overview over the major boundary conditions that need to be taken into account in the context of VenSpec.

The VenSpec science team is the core part of VenSpec, but funding by DLR to support this kind and scope of activity has to be tied to the provision of hardware. Therefore, the idea of a central control unit was conceived. A concept for a hardware-unit was established that would provide either added functionality to the instruments or offload engineering development from them. A trade-off study was performed to be able to define the scope of the hardware unit in such a way that eases the process of instrument development rather than burdening it by the addition of another formal as well as physical interface.

Formally, an instrument suite under a single instrument lead scientist might facilitate decision making, but the cost and technical complexity of each channel of the VenSpec suite made separate ILS-status a better option in order to secure funds and technical support from their respective national agencies (DLR for VenSpec-M, BELSPO for VenSpec-H and CNES for VenSpec-U). Therefore, the idea of a consortium under the lead of a single ILS was abandoned and all hardware units are developed independently under their own ILS . This gives the ILS full recognition from their funding agencies and full independence over the development of their instruments, which places the individual actors which have their expertise and their individual domains on equal footing. It nevertheless requires regular communication and significant commitment from all parties to ensure that common and democratic decision-making remains possible and productive at all times.

Building cutting-edge space instrumentation is a major undertaking for all institutions that becomes even more difficult for institutions that are not large in scale. The BIRA-IASB Institute has significant know-how in atmospheric research and technology development, but to bring the VenSpec-H project to fruition, significant TRL maturing as well as the inclusion of many other actors with additional technical expertise is necessary. The construction of the VenSpec consortium enables BIRA-IASB to focus on the most important elements in their instrument design, leaving other elements like compression to the central control unit.

IAA-CSIC, MPS and IDA provide either subsystems or full instruments to the major space missions on a regular basis, and are recognized actors in the field and longstanding partners of DLR. They have their own funding channels (e.g. AEI -Agencia Estatal de Investigación-, AEE -Agencia Espacial Española- and PRODEX programme, and the German Space Agency, respectively) and are therefore not subcontractors of DLR. In this way, DLR and the contributors to the CCU subsystems benefit from the synergies that have already been in place in many prior missions.

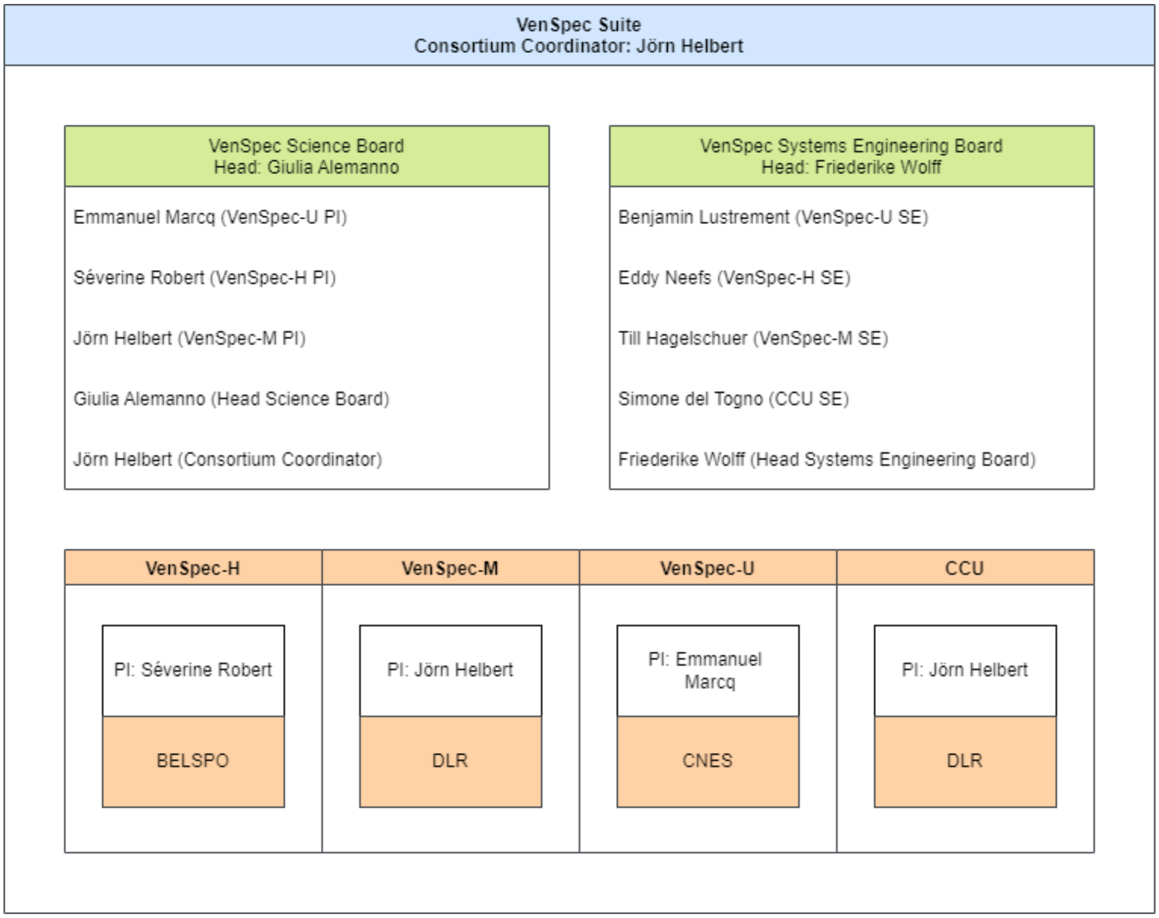
The Mauà Institute of Technology has already developed instrument simulators for the PLATO mission to facilitate interface verification of various parts of the spacecraft. For EnVision, the institute is going to build upon their previously acquired system and expertise in order to develop a simulator that will benefit the interface verification campaigns in Belgium, France and Germany before the flight units finally come together in Berlin. IMT, being a Brazilian institute, cannot export hardware to Europe, but will become part of a major European Instrument project by contributing by providing the manpower to conceptualize an design a high-quality instrument simulator and assemble it in Berlin after parts have been procured by DLR.

7. PROJECT DEFINITION, IMPLEMENTATION AND CURRENT STATUS

To ensure that the project does not become inflated beyond the point of being useful, its scope and boundaries have to be clearly defined, agreed and documented. The responsibilities have to be clear and complete to make sure guard rails are in place from the start and that all parties can rely on them for the entire duration of the project. The following describes various aspects of the consortium and the way they are implemented to support the vision of VenSpec.

Formal structure
In addition to the consortium lead, VenSpec has a science manager who supports the three ILs and the consortium lead in coordinating the joint science team, planning the science operations of the suite and tracking the science return of the consortium, which are the main goals of the consortium.

On the engineering side, one DLR team covers the CCU development and handles the VenSpec-level topics because of these topics are closely related. For phase B, this team was composed out of one manager, one system engineer, another system engineer working part time for the project and focusing on electrical topics, one AIV manager and one QA manager.



Synergies
The scientific topics on which collaboration is deemed to be important in addition to the main goals as defined above are in-orbit calibration and alignment. On-ground calibration is done independently for each instrument because different setups and approaches are required for the different parts of the electromagnetic spectrum. Operations scenarios are developed, agreed on and tested together, enabling the consortium to be science-ready at launch.
On the engineering front, electromagnetic compatibility and FDIR are major topics on which a common approach is sought, expertise is shared and verification is performed together.

Common documentation in the consortium currently consists of:

- power and data budget
- operations scenarios document
- calibration requirements
- alignment requirements
- schedule summary, risk register and management plan
- overall EICD
- AIV planning including the spacecraft AIV phase
- suite-level FDIR plan
- suite-level EMC plan
- suite-level PA plan

CCU hardware
The CCU is a separate electronic box which contains a cold-redundant set of a data-handling unit (DHU) and a power supply unit (PSU). It acts as the only electrical interface between the spectrometers and the spacecraft, providing power to the instruments, forwarding commands and telemetry, and provides compression of the scientific data as well as some top-level FDIR. A CCU architecture trade-off study was performed in 2023 which is presented in "Electrical integration of the VenSpec Spectrometer consortium: an architecture trade-off" (Alexander Fitzner et. al)

Formal engineering interfaces
The introduction of the CCU as an intermediate layer between the spacecraft and the instruments necessarily results in some added complexity relative to the usual approach of instruments interfacing directly and solely with ESA or the spacecraft. Since the instruments have their own ILSs, they formally deliver their instruments to ESA, but physically ship them to DLR to conduct final electrical, functional and EMC testing before delivery to the spacecraft. In terms of requirements and ICDs, the formal interface to the spacecraft system is split into two sets of requirements and interface documents, one of which is made applicable directly to the instruments or the CCU (e.g. mechanical and thermal requirements) while the other applies to the CCU (e.g. electrical and software) and which are flowed down to the channels via VenSpec-internal documents if applicable. This enables independent development and negotiation with ESA and the spacecraft prime where it is relevant while allowing the suite to act together on those topics for which it is necessary.

Collaborative Engineering
Electrons don't stop at formal boundaries and a combined electrical system necessitates collaborative solutions to anticipate and prevent problems. Therefore, the VenSpec engineering teams collaborate on designing for electromagnetic compatibility, dependability, in particular failure propagation, FDIR and encourage common part selection to the extent that is beneficial.

To share information as freely and rapidly as possible, VenSpec collaborates together on a common cloud server, where all information relating to the common topics of the suite as well as the detailed CCU documentation is stored. The consortium can access the information in real time without having to wait for formal releases from DLR, so that all parties have the latest information and feedback can be provided as quickly as possible. The exchange is covered by a very extensive NDA that covers all parties of the consortium and enables the sharing of technical data.

In addition to the normal working meetings, the full consortium convenes once per month remotely for two hours, every third meeting taking place in person and lasting three full days. In addition to the normal engineering work, workshops on specific relevant topics are conducted to enable information exchange and the sharing of approaches and lessons learned.

Verification approach
In order to ensure that interface verification can take place as early as possible, the following approaches are used to ensure that each party can test their system on their own prior to the final system test:

- each instrument will receive a EM-level CCU DHU with an EGSE to command it to be able to operate their instrument via the real interface even before the real hardware units are connected
- IMT will build a simulator with the capacity to simulate communication and commanding of the three instruments, so that software testing of the CCU can proceed early on
- full VenSpec-level functional as well as EMC testing will be conducted at DLR on breadboard level (pre-EM), EM, QM and FM to the extent possible
- the EM and FM suite are delivered to ESA after final verification has been performed

Intellectual property
Credit where credit is due, this also holds in the domain of scientific space missions. For the extensive sharing of data and know-how it is indispensable to agree on rules when it comes to intellectual property. Agreements have been made in the VenSpec consortium early on assuring that:

- any intellectual property will remain the property of the research organisation that contributes it to the project
- any intellectual property that comes into existence in connection with the VenSpec project will belong to the organisation which creates it.
- any intellectual property that is jointly created may be used freely by the involved organisations, subject to limitations on confidentiality

Operations planning

All three instruments of the VenSpec suite are mapping spectrometer with the goal of global coverage. None of the instruments are planning target observations and the operations of the instrument are tied to clear constraints. VenSpec-U observes on the dayside, VenSpec-M on the nightside and VenSpec-H performs observations on the day and nightside. All this combined means that the VenSpec suite has a very simple operational concept that require little to no short term adjustments unless there are unforeseen issues with the spacecraft.

Scientifically the datasets of the three instruments are independent but interconnected. To give a simple example - a volcano erupting on the surface of Venus would be detected by VenSpec-M from the thermal signature of the hot lava flow as well as from an enhancement of water vapor close to the surface. VenSpec-H would trace the emitted volcanic gases through the middle atmosphere up to the clouds and finally VenSpec-U would detect SO andd SO_2 above the clouds. In order to achieve this scientific observations the instrument need to observe at the same time looking at the same area, however there is no requirement for exactly matching of the observations.

The operation concept for VenSpec takes this into account. The suite will obtain data in 4 out of every 15 orbits. The suite will obtain dark calibrations at the same time as this requires pointing of the planet into dark space and VenSpec-H and -U will obtain sun calibration at the same time (with VenSpec-M not operating). Operations will be coordinated across the suite on the timeline level. Whether the suite will deliver in the end one combined VenSpec timeline or three coordinated instrument timelines is subject of further discussion with the ESA operation team.

Limits of the VenSpec organization

This approach ties together very closely instruments that are developed independently and which are expected to encounter significant challenges during their implementation phase. At the same time, the VenSpec-level responsible have no executive power: decisions and agreements are purely consensus-based. Therefore, it is paramount to establish what VenSpec can reasonably achieve and agree upfront on where responsibilities lie. Another major point is to enable ESA and the spacecraft to understand who is responsible for what and who is the relevant spokesman and responsible for each issue. To ensure the implementation phase is conducted in an efficient way and to make sure all problems are adequately addressed, the VenSpec Systems Engineering Board (SEB) was established. It is composed out of the system engineers for all instruments, the CCU as well as the head of the board (DLR). Major points of concern at the spacecraft level are schedule and budgets, therefore, VenSpec keeps a schedule summary as well as mass, data and power budgets for the entire suite to provide an overview of the status of the individual teams. Since the SEB has no formal executive power, the SEB releases this common documentation with the goal of providing information to ESA that is harmonized, enables comparison between the units and acts as an intermediary that follows the developments of the instruments more closely than a payload manager could. Due to the additional insight and resources DLR brings to the engineering team of the suite, the head of the SEB commits to flagging concerns to ESA, prioritizing problems, and agreeing on a sensible and acceptable resource allocation. The benefit for ESA is that they are interfacing with a single entity rather than three very similar but different entities, which might use terminology in different ways, have different margin philosophies or choose different approaches to the same problem even if harmonization would have been possible. In some cases, common and harmonized documentation facilitates finding information, enabling more effective oversight and forwarding information to the spacecraft contractor.

8. CONCLUSION AND OUTLOOK

The VenSpec consortium leaves the individual actors the freedom necessary to efficiently develop their scientific instrument, but the collaborative aspect does demand a significant mindset shift of all actors relative to that of a typical instrument. To keep in mind that collaboration is the default, to discuss with the suite and reach a consensus with other entities on equal footing is always an upfront investment, the real fruits of which we will only reap many years into the future. The promise of VenSpec is to provide an organizational framework tailored to its cause, but that is novel to all VenSpec parties as well as to ESA and the prime contractor. Sometimes, this novelty can seem incoherent and confusing, and all stakeholders must be reminded that from a higher vantage point, all formal processes are to some extent arbitrary and become intuitive by virtue of being well-rehearsed. With the long timescales in the EnVision project that foresees iPDR in 2025, iCDR in 2027, flight model delivery in 2029 and a launch at the end of 2031, all processes in VenSpec will have sufficiently matured to handle the pressure of the more exacting implementation phase when the time comes. VenSpec as a whole stands behind the vision of being a common team and looks forward to meeting the challenges the future of the EnVision project beholds.

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