HIGHLY INTEGRATED PAYLOAD ARCHITECTURES AND INSTRUMENTATION FOR FUTURE PLANETARY MISSIONS

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ABSTRACT

Future planetary missions will require advanced, smart, low resource payloads (P/Ls) and satellites[1,2] to enable the exploration of the solar system in a more frequent, timely and multi-mission manner within a reasonable cost envelope. The concept of highly integrated payload architectures was introduced during the re-assessment of the payload of the BepiColombo Mercury Planetary Orbiter. Considerable mass and power savings were achieved throughout the instrumentation by better definition of the instruments design[3], higher integration and identification of resource drivers[3]. Higher integration and associated synergy effects permit optimisation of the payload performance at minimum resource requirements while meeting demanding science requirements. This promising concept has been applied to a set of hypothetical Planetary Technical Reference Studies[5,11] (PTRS) on missions to Venus[6], Jupiter/Europa[7], Deimos[8], Mars[9] and the investigation of the Interstellar Heliopause[10]. The needs on future instrumentation were investigated for these mission concepts and potential instruments were proposed[11]. The result of the study is discussed here in the context of future technology requirements that are related to micro- and nanotechnologies.

1. INTRODUCTION

Motivation for the development of small space crafts (S/Cs) and highly integrated P/L architectures has been presented earlier[3]. We summarise the following key objectives of miniaturised and highly integrated S/C and P/L architectures:

I. Reduced mission preparation time
II. Smaller effective project & industrial teams
III. Simplified interfaces and standardisation
IV. System level aspects are addressed in a timely and multi-mission manner
V. Reduced number of different components (space qualification facilitated)
VI. Reduced launch costs (e.g. Soyuz, DNEPR, Piggyback)
VII. More frequent and faster launch possibilities
VIII. Use for educational purposes and technology demonstrations

In order to refine the highly integrated payload architectures concept we have taken two approaches to investigate this concept in more detail:

For the **first** investigation or approach we have taken a set of instruments of the BepiColombo MPO payload as a reference. A selection of instruments being of generic nature and potentially of use for other future planetary missions has been proposed and investigated for its suitability for integration and miniaturization. For this payload a detailed electro- and opto-mechanical design based on a Highly Integrated Payload Suite (HIPS) concept has been derived. The selected group that has been studied further consists of the following six instruments:

1. High Resolution color Camera (HRC),
2. Stereoscopic Camera (S-Cam),
3. Laser Altimeter (LAT),
4. Radiometric Imaging Mapping Spectrometer (R-IMS),
5. Visible Near Infrared Spectrometer (VN-IMS),
6. UV spectrometer (UVS)

Further details on the instrumentation can be found in the BepiColombo Payload Definition Document or in ref. 3 and 12.

The **second** approach investigated the payload of a set of technical reference studies for its potential of integration and miniaturisations. Technology Reference Studies are mission studies, that are not part of the ESA science program, but which have the purpose to identify the technical development requirements for potential future

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scientific missions. For planetary exploration, the primary objective is to explore ways to decrease cost and risk by studying the feasibility of small satellite missions, which would allow a phased and systematic approach to the exploration of the planetary bodies of the solar system. The studies were selected to address a wide range of challenging technologies for future exploration of the solar system. The following PTRSs are currently under study:

1. **Jovian Minisat Explorer** – a mission to Jupiter's moon Europa
2. **Venus Entry Probe** – an Aerobot for in-situ exploration of the Venus atmosphere
3. **Interstellar Heliopause Probe** – a probe into the interstellar medium towards the bow shock
4. **Deimos Sample Return** – a zero gravity landing manoeuvre to bring back 1 kg from the moon of Mars
5. **MiniMarsExpress** – small sat mission comparative to Mars Express

More details on the complete mission scenario, including S/C, launch, cruise, communication, orbit and their feasibility, can be found in ref. [6,7,8,9]. Similarities of the payload requirements are investigated so as to derive a road map of technology developments which are required to enable the presented mission concepts, where all spacecrafts are to be launched as a single or double composite on-board a Soyuz-Fregat SF-2B launched from French Guyana. An overview of the different types of instruments that were part of the strawman payload of the mentioned study missions is given Figure 1.

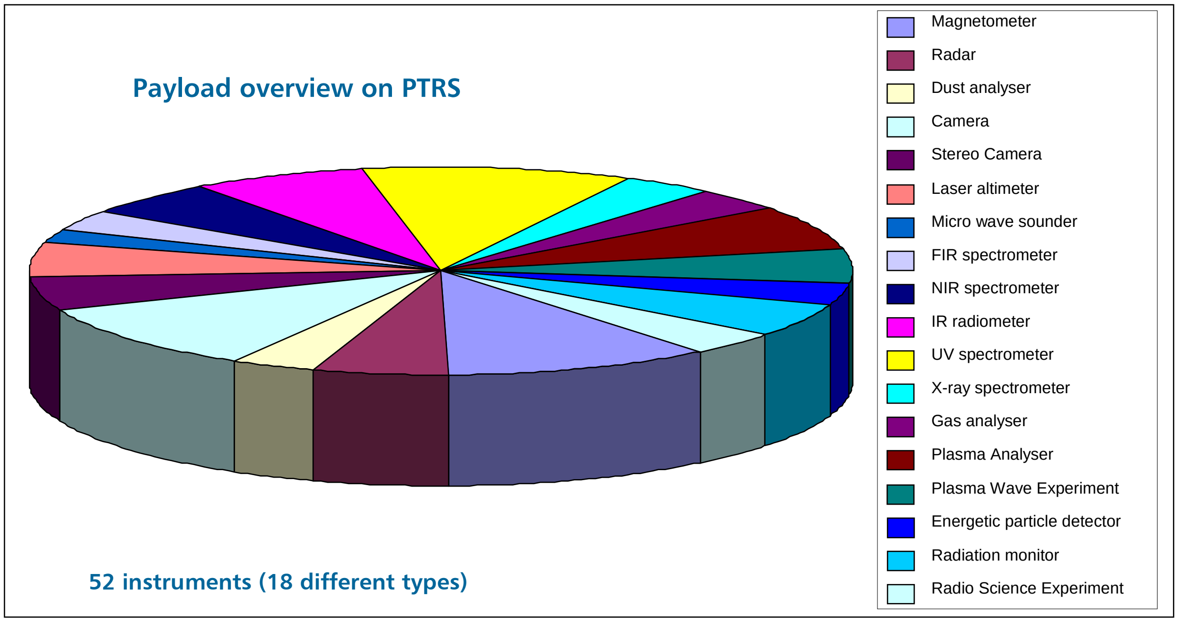

Figure 1 Overview of the strawman payload that was selected for the planetary technical reference studies (PTRS).

2. OVERVIEW ON PAYLOAD REQUIREMENTS FOR PLANETARY MISSIONS

The studied reference missions and the BepiColombo mission were selected so as to provide a reasonable amount of representative configurations that would give insight in the technical challenges for instrumentation of the future. The HIPS concept has been identified as a possible way of implementing payload as an integrated suite on a low resource S/C for future planetary missions. It plays an important role in enabling such ambitious missions as a European undertaking. Cost constraints demand the establishment of effective teams that can, within a sufficiently short timescale, design, construct and build payloads, taking advantage of the appropriate system level know-how to avoid delays on tight schedules. This requires a tight management and coordination of several activities. Due to the high integration and complexity of the suites, the technical management of such complex suites is challenging and must be demonstrated on a sufficiently realistic and complicated case that is representative of future flight projects. For that reason we have selected the payload of the BepiColombo mission and the aforementioned hypothetical study missions for this investigation. For further considerations, the requirements are separated into remote sensing and in-situ instrumentations for which we give a short overview and impression with respect to the relevance of the identified technology needs.

2.1. Remote sensing instrumentation

Remote sensing payload may cover a broad range of instrumentation that extends over a large spectral range from long wavelengths such as used in active radar observations up to short wavelengths enabling passive detection of high energy radiation for which practically mass limited detectors still have enough cross-sections or stopping power. Furthermore the payload may be classified into two categories, one that senses photons and another that detects and characterises particles. High energy particle detectors may be considered as remote sensing instruments since they provide information from a source far away from the S/C; low energy particle detectors probe the environment and are therefore considered as in-situ instrumentation. We start to describe the instrumentation from the low energy to the high energy range. Here, no emphasis is put on the miniaturisation of the processing electronics which is subject of other investigations. It shall be noted in general, that instrumentation dedicated for long wavelengths bears in principle the potential for integration of instrumentation that employs shorter wavelengths.

Radar: Planetary probes often want to collect information of the inside of the body. This is only possible if a sufficient long wavelengths are used that allows sufficient penetration into the body. As a consequence the receiver antenna needs to be as long as the wavelength, which is a few 10 m. Miniaturisation relies therefore on extremely light structures that do not influence the navigation of the S/C and that are very stiff so as to have no low frequent resonance frequencies. Future developments are expected to focus on light structures or the integration of antennas in other functional units such as solar arrays.

Micro-wave sounders: MWS are powerful tools that gather information from the surface, subsurface and consistency of the atmosphere of a planet. Receiver dishes may be as small as a few 10 cm and are considered as feasible. Modern emitter and receiver electronics enable sufficiently low resources for MWS so that they may be considered as feasible within low resource missions.

Infrared spectrometers and radiometers: Spectrometers operating in the NIR and MIR region are subject to miniaturisation and shall become as sensitive as necessary for the exploration of planetary surfaces and atmospheres. Small pixel arrays are crucial to achieve highly resolved mapping information. NIR spectrometers operate mostly at modest cooling temperatures achieved by electrical cooling and MIR room temperature bolometers can be operated uncooled with very low resources. Micro-coolers are important for highly sensitive applications and would allow higher efficiencies where required. Optical elements such as patch filters or linear filters rely on advanced processing technologies that need to be developed further. Optical elements can be produced by diamond turning and dead reckoning methods. IR spectrometers may be subject to high integration and should be able to cover spectral ranges from the visible to the FIR region. The spectral imaging can in principle extend until the visible region. An example of a broadband and highly integrated spectrometer will be presented below.

Visible cameras, spectrometers and altimeters: Cameras used for the observation of a planetary surface shall often supply not only imaging information but also colour information to determine its albedo or to investigate certain mineralogical features extending from the visible to the near infrared. This requires sensors equipped with filters of ~10nm spectral width which are ideally placed directly on the detector. The choice of the wavelengths of the bands changes with every mission depending on the surface consistence. Technologies that allow the direct placement of filters on the detector hardly exist. Active pixel sensors are radiation hard and may be equipped with ASICs so that they consume little power and accommodation space. The main drawback is that the readout noise is slightly higher than for CCDs. Since imaging of the surface usually is coupled to altimetry so as to derive absolute information on the topography, the integration of cameras and altimeters using the same view port and providing information from the same ground element seems to be obvious. We have chosen this as another subject of investigation.

UV spectrometers and photometers: Photometers are employed if only a few or a single emission lines are subject of interest. In such cases photometers are well suited for observation. For the detection of weak lines, a concentration or collection of the light is required. This can be achieved by the use of micropore optics. The resulting instrument may be very small and if detectors can be miniaturised as well, then photometers can be very compact. Spectrometers instead need dispersion of the light. This suffers typically from the inability to produce detectors with broad sensitivity (single photon counting) covering several decades of the spectrum. The same applies to the dispersive element, which is usually a grating that may be subject to order sorting problems. Filtering technologies may solve this problem. Common to both types is that straylight rejection is often the most demanding requirement, a problem being identified also for X-ray instrumentation. Resource reduction could be made by miniaturization of baffles by use of micropore technologies.

X-ray spectrometers: Similar requirements as for UV instrumentation apply for X-ray instrumentation except that the dispersion of the radiation is performed by the detector itself since the energy of the photon is sufficient to generate a charge sensitive readout that may determine the photon energy. Room temperature detectors with large bandgap materials such as GaAs need to be developed to avoid cooling. Pulse height analysis of the generated signals within large arrays requires ASICs for a larger number of channels, typically ~64x64. No particular reason is identified why X-ray spectrometers should not be integrated, although large focal lengths do not facilitate easy implementation. This is clearly calling for a separation of the detector and the optics on the S/C. Also here micropore optics are most promising for imaging applications.

High energy detectors: Low resource missions can hardly afford cryogenic cooling so that semiconductor detectors with high resolution are prohibitive. Instead scintillation detectors are proposed that have sufficient stopping power and resolution. With appropriately miniaturised electronics, high energy detectors or radiation monitors can be built at moderate resource requirements.

2.2. In-situ instrumentation

Miniaturisation of instrumentation for in-situ applications is even more grateful since the physical limitations are less stringent and instruments may be small. This is counter balanced since the available resources are even more restricted so that the degree of miniaturisation needs to be extremely high. The application range covers mini-spectrometers for electromagnetic radiation or fields, charged particles and chemicals. Also here the whole spectrum from the FIR to highly energetic particles or photons may be employed in active or passive measurement techniques. In this paper we do not further discuss in-situ instrumentation, although we conclude that highly integrated instrumentation is mandatory.

We present a comprehensive overview of the required technologies in Figure 2. It must be noted that the list that is given here is certainly not complete. Nevertheless, it gives an overview of items that have been identified to be of use for the production of highly integrated instrumentation. The payload engineers can hardly find a suitable pool of instrument components that are considered as affordable, flexible for adaptations and space qualified. Pools of components exist in the electronics area but not for instrument components, which is usually intellectual property of individual expert groups, companies or institutes.

Technology	Item	Comment
Structures	Deployable large antennae (subsurface radar) and deployable booms	Caron fibre, light weighted, clever deployment
	Advanced instrument structures and materials	CSiC, composites, reinforced plastics, etc.
	Smart baffles reflecting thermal heat	Be, AlBeMet, diamond turning
Optical	Beam splitters	Efficient, flexible cut-off
	Linear variable filters	VIS to MIR
	Interference filters	tunable wavelengths, integrated onto sensors
	VIS and FIR patch filters with small structures	gapless design
Fibre	Optical fibres and bundles	
	Coupling technologies	Small
	Micro-collimators, baffles	Optional coating, blackening
Sensors	Active pixel sensors – large arrays, small pixels, VIS-NIR	Low power sensors, (CMOS technology – radiation hard)
	Microchannel plates	Compact, high spatial resolution, high QE, broad band
	Microbolometers	Small pixels, high NEDT
	Micro coolers or efficient radiators for passively cooled	Low noise, low power
	Photon counting high QE sensor arrays	Visible spectral range, high speed, gating
Microchips	Meteorological micro package	Thermometers, pressure, humidity, etc.
	Inertial micro package	Accelerometers, gyros, etc.
	Microchip lasers	High output power,high efficiency
Electronics	Field Programmable Gate Arrays (FPGAs)	High density of gates, redundancy
	Application Specific Integrated Circuits (ASICs)	Only for generic electronics
	Miniaturised low power Data Processing Unit	Scalable architecture to serve different processing demands
	Low power broad band bus system	SpaceWire, CAN
	Central power supply system, low power DC/DC converters	Power management
	Radiation hard electronics	Extreme thin film technologies

Figure 2 Overview of several identified technologies that facilitate high integration levels and miniaturization.

3. HIGHLY INTEGRATED BROADBAND IMAGING SPECTROMETER (HIBRIS)

One of our study objects was the combination of a NIR and a FIR mapping spectrometer that may also be used in a radiometric mode. HIBRIS is a combination of three instruments that cover a spectral range from 0.7 to 60 μm. The type of NIR spectrometer is considered as generic instrument being suitable for many missions. For the planetary reference studies these were: JEO[7], VEP[6], MEX[9] and potentially DSR[8] or the recent concurrent design facility study mission NEO-2.

A linear variable filter concept in the NIR range has been identified as a very compact solution that avoids the use of gratings, which are usually limited to one decade of spectral range or even less. HIBRIS will employ such filters and allows the performance investigation of these filters in practical use. The instrument shall be used to verify the performance of the sensor that is developed for BC under the ESA-TRP programme. The aim is to focus on system level verification of the sensor and to identify potential difficulties at an early stage. HIBRIS is designed and could be built similar to the BC R-IMS and VN-IMS. HIBRIS is a suitable platform on which to test the HIPS concept, particularly the electronics, data handling and power aspects. HIBRIS has an innovative optical design, such as to reduce the mass and power required for HIBRIS. The key innovations are:

I. Use of **linear variable filters for different spectral ranges**. These can remove the need for a separate spectrometer section (HIBRIS-SWIR), which provides a substantial mass saving. The relatively low spectral resolutions of BepiColombo, typical of a mission to a planet without a dense atmosphere, encourage such an approach. Two linear variable filters for the spectral ranges 0.9 to 1.7 µm and 1.3 to 2.5 µm are foreseen. For the TIR spectral range one linear variable filter from 7 to 14 µm will be employed. Typically LVFs can cover a wavelength range slightly less than λ to 2λ, with a resolution of up to about 1% of the centre wavelength. The dimension of an LVF in the spectrally-varying direction does not fall much below 10 mm.

II. A single **microbolometer array** that covers a large wavelength range. This potentially removes the need for additional detectors and transfer optics, leading to a saving in mass, power and a reduction in complexity. This is made possible also through the use of linear variable filters, and the innovations are therefore complementary. Such bolometers are available to date at 320×240 pixel configuration with 35 µm pitch, a time constant of 11 ms and a NETD of 30 mK at 300 K, F/1 and 50 Hz. The best of the currently-available arrays with 35 µm pitch has an NETD of 45 mK.

III. A photovoltaic SWIR detector that is supplied in a dewar, the window of which provides out-of-band blocking. Unlike the TIR detector, the SWIR detector can operate under normal pressure, but measures have to be taken to avoid condensation on the cold detector surface. Such detectors have excellent qualities between 1 to 2.5 µm (primarily low dark current, when thermoelectrically cooled and high quantum efficiency) and will be used.

IV. Combining instruments using an innovative broadband and ghost-free **ITO beam splitter**. Although this approach reduces mass in a dramatic fashion, it has several potential disadvantages: a loss of redundancy, a loss in flexibility in operations, an added complexity in assembly and testing. Making the HIBRIS design modular mitigates the last point.

V. **Mesh filters** that consist of stacks of metallic meshes pressed together with a polypropylene substrate. Three mesh filters covering 30 to 35, 35 to 40 and 40 to 45 µm are used for the radiometric part of HIBRIS.

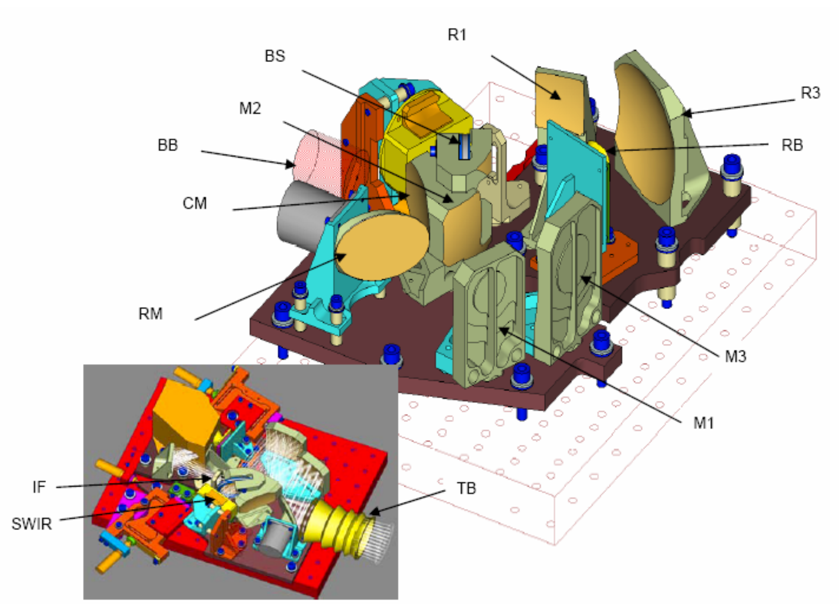

Figure 3 Mechanical design of HIBRIS with all its components indicated as follows: BB: calibration blackbody, BS: beam-splitter, CM: calibration mirror, M1-3: 3 mirrors comprising HIBRIS front-end telescope, R1-3: 3 mirrors comprising HIBRIS re-imaging optics, RB: radiometric baffle, enclosing micro-bolometer detector of HIBRIS-TIR, SW: switching mirror, SWIR: short wave infrared detector assembly, TB: thermal heat-rejecting baffle, IF: intermediate filter.

4. STEREO IMAGING LASER ALTIMETER (SILAT)

4.1 Key innovations

An integrated high resolution camera and altimeter package has been designed because of stringent co-alignment requirements between the HRC and the LAT, and between HRC and SCAM. Common optical systems and common electronic systems for the HRC and the SCAM are required. Miniaturisation of the sensors, the optical elements and the electronics facilitate greatly the integration of subunits. APS detectors for the SCAM and HRC, which have sufficiently high readout speed, controllable short exposure times, radiation hardness and binning functionality are employed. FPGA based electronics that communicates via SpaceWire will provide a first miniaturized approach that may be further developed by ASIC production. A photon counting concept for the laser altimeter is foreseen. A single photon shall give sufficient information on the distance to the planet if identified properly. This minimizes the laser power and the load on the optics. Enabling technology are **Single Photon Avalanche Detectors** (SPADs) or **Silicon photomultipliers**, **fibre technologies** and a high-power **microchip laser**.

4.2 Micro laser altimeter

The concept of the micro-laser altimeter (LAT) is based on photon counting, which has no space heritage yet, albeit having been successfully demonstrated several times on Earth. TRS's like the Jovian Europa Orbiter and the Deimos Sample Return would profit from such instrument technology. Also landing on planets or missions to an asteroid or on comets may use it for navigation purpose and topographical investigations. No scanning mechanism is foreseen so far, but future investigations could explore **adaptive optics** implemented as **MEMS** to realise this objective. The LAT-TX laser is generating a high frequency train of light pulses that are focused onto a small spot on the surface of a planet. The electronics has to provide for every "shot" a start time that is delivered to the LAT-RX electronics.

4.3 Laser source

Currently there exists no heritage for space qualified, high powered, high repetition rate diode pumped passive Q-switched Microchip lasers. Some MicroChip lasers are currently in use or under investigation for other ESTEC projects, but the suppliers frequently stop manufacture of these particular types of laser. To demonstrate the feasibility of a photon counting LAT in the scope of a breadboard a 25 μJ Microchip laser system with a pulse repetition of 10 kHz and a pulse length of 1 ns is needed. The development of such a laser source for the LAT-TX shall be split into two separate tasks, the development of a small laser head suitable for space application under hard radiation environments, and the development of small, efficient and lightweight driver electronics. For the first breadboard commercial-off-the-shelf (COTS) lasers, which have a small laser head, but relatively large driver boards, can be used. This will allow for the verification of the photon counting LAT principle, its dependence on different laser parameters such as wavelength, repetition rate and energy, the sensibility of the optics to temperature gradients and functionality of the fibre coupling. At a later stage a more powerful laser system can be used. The laser source will be equipped with a standard FC fibre coupling mechanism for single mode fibres.

4.4 LAT-RX

The LAT receiver consists of three parts: The optical system, the detector and the control electronics that measures the time-of-flight and hosts the correlation range receiver. Expanding the HRC FOV and accommodation of a pinhole in the focal plane of the HRC are required. This pinhole of 40 μm diameter will be used as a field stop behind the spectral filter. It will be attached to the LAT-RX filter plane and has to be aligned with a 1.5 mm diameter hole in the HRC PCB. A set of rectangular plates with different size holes with a diameter between 15 and 200 μm will be used to ease alignment. Rectangular outer shape of the plates facilitates alignment and mounting. For the breadboard of the LAT-RX a multi mode fibre of 1 m length will be used to transport the light passing the hole in the PCB to the detector. Due to its proximity to the pinhole the angular cone of light that will enter the fibre is limited and a numerical aperture (NA) of 0.2 is sufficient for the fibre. To further ease alignment requirements a fibre with a NA of 0.3 will be chosen. The narrow space and close proximity to the FPGA on the backside of the HRC prohibits any alignment mechanism and will make it necessary to glue the fibre directly into the PCB. A COTS Si Single Photon Avalanche Detector (SPAD) is the baseline for the initial LAT-RX breadboard. The SPAD will use on- chip active quenching circuits that reduce the dead time to 40 ns. The LAT design also takes into account the later application of pixelated arrays. Si photomultipliers that are currently under development are considered as potential solution that would allow high fillfactors and small pixels.

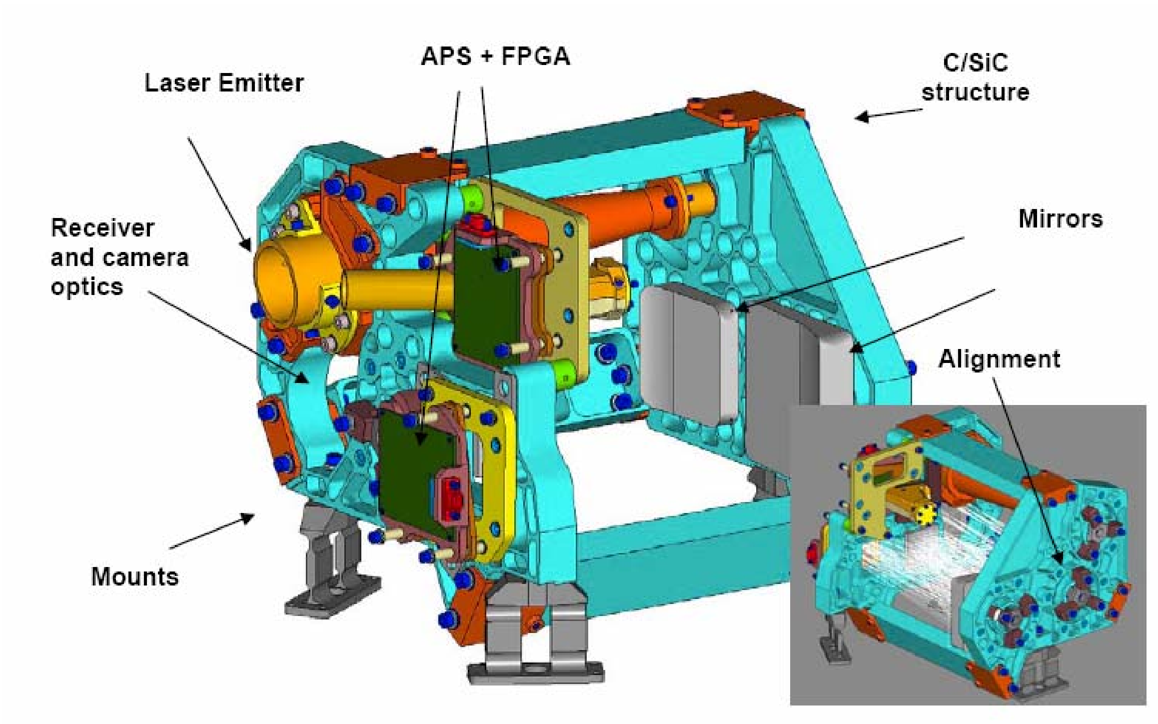

Figure 4 Mechanical layout of the Stereo Imaging Laser ALTimeter (SILAT). Not shown here are thermal and straylight baffles, the laser source and its power supply. The insert shows the SILAT from the backside. The dimensions of SILAT are 220 x 160 x 150 mm^3.

5. INSTRUMENT INTEGRATION

A rather tight assembly and integration space is expected. The general outline and design of the instruments are shown in Figure 4 and Figure 5. An Ultraviolet Spectrometer (UVS) is identified in our studies as another key instrument for planetary missions. The UVS is shown on the opposite side from HIBRIS and SILAT. The UVS structure is monolithically aluminium, including mirrors. A different HIPS configuration, in which more than one instrument in the UVS attitude is required, might take advantage of a second bench normal to the first; the attachment of the two benches is similar to the attachment of the UVS to the breadboard (see Figure 5). Another instrument of interest, the Neutral Particle Analyser (NPA) involves neutral particle detection, electrons and ion detection with different energy ranges. Plasma sensors have been developed in the past for Mars Express and are under development for BepiColombo. The sensors are very sophisticated and largely miniaturised. Any of those instruments can be added easily to the payload suite if interfaces are standardised. A matured design of a highly integrated payload suite has been generated that may be used as feasibility demonstration of miniaturised payloads for low resource planetary missions.

6. DISCUSSION AND CONCLUSION

Assembly and integration of so many functionalities impaired with very high co-alignment requirements poses a high demand on the instrument engineers regarding the AIV. The production of HIPS is therefore considered as demanding task that is experienced as a challenge. Microtechnologies are expected to be a key in further developments that allow gaining space for the integration of multiple subunits. Implementation of other instruments is possible by modular design.

The suite consists of a number of instruments that are representative in complexity and performance of scientific instruments required for challenging planetary exploration missions. Such an instrument suite could, without major modifications, be sent to many planets and moons, comets and asteroids for remote sensing exploration of their surfaces. The presented consolidated optical, mechanical, and electrical design and the system engineering, is considered to be ready for laboratory implementation and further performance evaluation. Further architecture refinement, identification of bottlenecks or difficulties in the implementation of the highly miniaturised electronics, sensors and remote sensing concepts can be found and solved only during a proposed breadboard development. The potential of Micro- and Nanotechnologies can be further investigated during this course and it should be mentioned that in-situ payloads benefit largely as well from those technologies.

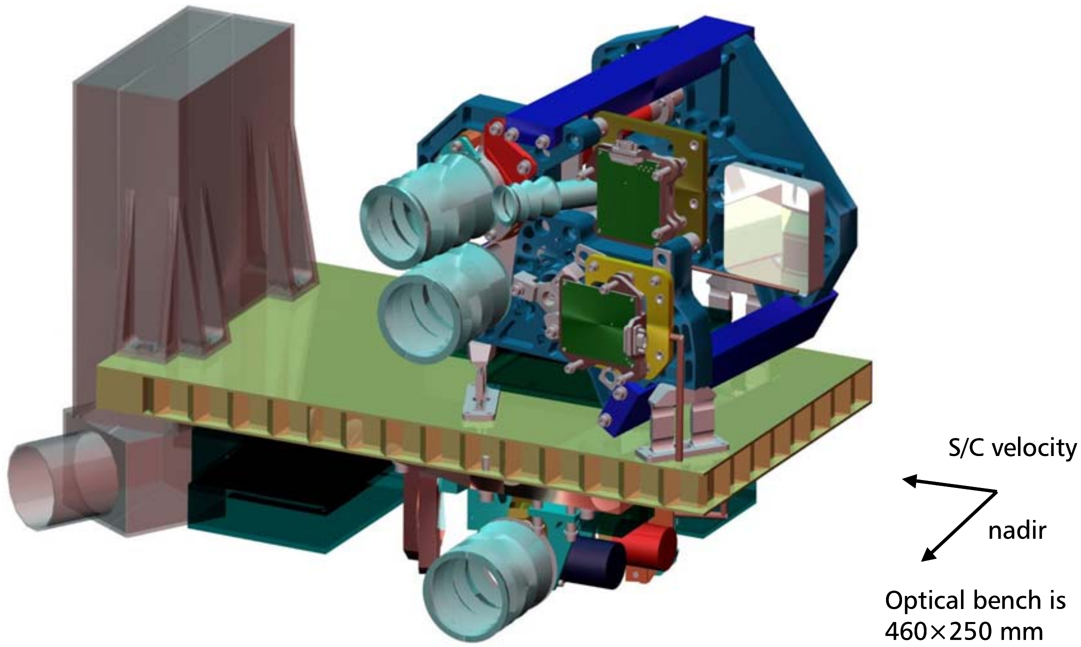

Figure 5 Possible HIPS instrument configuration of SILAT, HIBRIS and UVS. Other instruments can be implemented as well on demand.

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