

Design and testing of a sample handling system for operation on the lunar surface

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Abstract—Here we provide an in-depth description of the design concepts and verification strategy for the sample handling system (SHS) used for preparing lunar regolith samples for analysis by laser ablation ionization mass spectrometry (LIMS).

The SHS is an integral part of a reflectron-type time-of-flight LIMS (RTOF-LIMS) system that allows for direct and sensitive chemical composition analysis of individual regolith grains *in-situ* on the lunar surface. The RTOF-LIMS measurements can provide the full element and isotope composition of the sample material (mass range up to $m/z \sim 1,000$) for each individual laser pulse applied to the sample surface.

The CLPS-LIMS instrument is manifested for a robotic mission (stationary lander) within NASA's Artemis Commercial Lunar Payload Service (CLPS) program to the lunar south-pole. The lander will provide upon request lunar regolith (grain sizes ≤ 5 mm) to the LIMS instrument's collection funnel for further sample manipulation by the instrument. The sample material is

sieved in a two-stage process assisted by vibrating the funnel and sieve assembly at their first global resonance frequency. The sieving process removes grains with particle sizes larger than 1 mm, as these would interfere with achieving the required sample surface quality for reliable LIMS measurements. Control of the sample roughness is important to ensure consistent laser ablation conditions during sample analysis and thus reproducible chemical composition determination of the sample material.

The sieved sample material is deposited into a 1.5 mm deep and 5 mm wide channel at the edge of a rotating circular carousel disk with a diameter of 187 mm. The system creates, with the help of passive shaping brushes and a skimmer blade, a well-defined planar sample surface with height variations less than $\pm 200 \mu\text{m}$ in $> 90\%$ of the conducted test runs. After chemical analysis by LIMS, cleaning brushes remove the remaining material from the channel and prepare it for new sample material delivered by the lander platform. The SHS system allows for indefinite sample material to be analyzed. Two

reference samples are included along the edge of the carousel for calibration purposes of the chemical analysis performed by the LIMS instrument.

The SHS was tested and validated at inclinations up to $\pm 10^\circ$ off the nominal plane of operation, as an angled landing position of the lunar lander is possible. The observed overall sample utilization efficiency was influenced by losses during sieving and the intentional overfilling of the carousel channel. Effects on the sample surface quality have been studied and found to be within the requirements for subsequent analysis of the regolith by LIMS. Tests were conducted using regolith simulant with grain sizes of up to 5 mm (LHS-2, Space Resource Technologies, USA, complemented with larger grains). To test sieving efficiencies in the lunar gravity environment, cork grains with low specific mass were used to simulate the reduced gravity. Finite element analysis of the SHS shows compatibility with vibration loads as defined by NASA's General Environment Verification Standard (GEVS).

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1. INTRODUCTION

A Laser Ionization Mass Spectrometry (LIMS) instrument, designed to analyze the chemical composition of samples collected during an upcoming lunar mission, is currently under development. The LIMS instrument will operate on a robotic lander platform for conducting autonomous in situ measurements of lunar mineralogy, element composition, and isotope distribution without human intervention.

As part of NASA's Artemis program and its Commercial Lunar Payload Services (CLPS) framework, our team is working on developing the instrument, named "CLPS-LIMS", for upcoming missions with landing sites near the lunar south pole.

A major scientific goal of the Artemis program as outlined in the Artemis III Science Definition Team (SDT) report [1] is improving our understanding of the Earth-Moon system, such as the formation history and evolution of the Moon [2], [3]. Also, the lunar surface can serve as a time capsule preserving the history of impactors which were hitting the early Earth [4], [5], [6]. Sensitive chemical composition analyses and determination of isotope ratios of the lunar regolith grains will allow for a better understanding of the geochemical environment of the landing site [7]. These investigations

directly address some of the questions formulated in the SDT report. Additionally, for a permanent human settlement on the lunar surface, local resources will have to be exploited [8] referred to as *in-situ* resource utilization (ISRU). To select, e.g., suitable building materials, the chemical makeup must be known [9], [10], [11]. The CLPS-LIMS instrument will deliver chemical composition information of bulk regolith as well as single grains.

The CLPS-LIMS instrument employs a pulsed laser system in conjunction with a mass analyzer to study the chemical composition of lunar regolith [12]. The laser beam is focused onto the sample surface to spot sizes of about 20 μm in diameter, resulting in irradiances in the range of MW/cm^2 to GW/cm^2 , leading to ablation and simultaneous ionization of the material. The mass analyzer is based on a reflectron-type time-of-flight mass spectrometer (RTOF-MS) ion optical design [13], [14], [15]. The laser pulses are generated by a Nd:YAG microchip laser system employing second-harmonics generation ($\lambda = 532 \text{ nm}$, $\tau \sim 1.5 \text{ ns}$, 100 Hz pulse repetition rate). For a more in-depth description of the instrument's subunits, we refer the reader to the previously published studies [16], [17].

Instrument overview—A programmatic constraint of the mission is the strict adherence to the mechanical shock and vibration loads as defined by the General Environmental Verification Standard (GEVS) [18]. This is to decouple the requirements the payloads must fulfill from the, yet unknown, specific load environment the payloads will be subjected to during launch, transit and landing. This constraint excludes the possibility of a spacecraft (S/C) coupled loads analysis and the option to notch random loads at the S/C interface in case of high accelerations.

The instrument design published in [17] used a base structure (Main Support Structure, MSS) made of aluminum honeycombs sandwiched between near-zero coefficient of thermal expansion (CTE) carbon fiber-reinforced plastic (CFRP) sheets. These sheets provide the S/C interface as well as the mounting points of the different subassemblies. Structural finite element (FEM) analysis of this Spectrometer Unit (SMU) design (quasistatic analysis and full random analysis) showed structural loads at subassemblies exceeding limits when using input loads as specified by GEVS at the S/C interface as simulation input. The main cause identified was the 0-CTE structure highly amplifying the input loads. As targeted notching is out of scope, reducing the observed loads is only possible through structural changes to the MSS. Investigated design options were either stiffening the MSS and thus shifting the eigenfrequencies higher or softening the MSS to lower the eigenfrequencies. Both variants had the common goal to shift the MSS's eigenfrequencies into regions where GEVS input loads are lower. None of these approaches was successful and, consequently, a completely new mechanical design of the MSS became necessary. The new concept is based on a monolithic structure fabricated out

of AlBeMet AM162. The material choice was based on the need for a thermally and mechanically stable, but lightweight structure. High thermal conductivity and heat capacity allow for uniform thermalization of the structure. Its mechanical characteristics, combined with its low CTE, make AlBeMet a good choice for a structure that must meet strict mechanical tolerances while being subjected to thermal changes. Additionally, AlBeMet's specific stiffness is higher than Aluminum or Titanium, making it more suitable for construction of GEVS loads compatible structures.

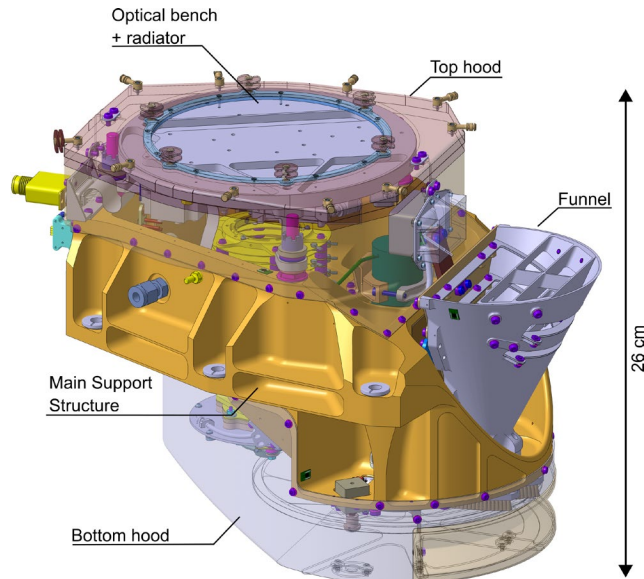


Figure 1: Overview of the current SMU design of the CLPS-LIMS instrument with a main support structure (MSS) fabricated out of AlBeMet AM162.

This monolithic design of the SMU is shown in Figure 1. The AlBeMet MSS is depicted in orange. All subassemblies, such as the mass analyzer (MA), the optical sub-system (OSS) and the sample handling system (SHS), are directly mounted to the MSS. The spacecraft interface is realized via inserts made of Ti6Al4V (Grade 5). These are individually dimensioned to compensate for residual machining tolerances of the MSS and pressed into the AlBeMet structure. The main design requirement was the need to keep random load amplifications at the subassemblies minimal. As the GEVS input loads prescribe high acceleration spectral densities between 50 Hz and 800 Hz [18], a minimum eigenfrequency of > 2000 Hz was defined for the MSS. Weight optimization of the MSS was performed using a geometry optimizer in combination with FEM analysis.

The SMU is encased in lightweight hoods fabricated out of glass fiber reinforced polymer (GFRP) for protection from lunar dust to which multilayer insulation (MLI) is attached via standoffs, serving as thermal barrier.

Radiative surfaces for heat dissipation serve multiple purposes. The optical bench (see Figure 1) functions simultaneously as the radiative surface for the laser and associated optics. To dissipate the heat produced by

components within the SHS, the funnel on the SMU's side is used.

In a previous publication [17], we discussed the general sample handling concept of the CLPS-LIMS instrument. Since then, this concept has been refined and extensively tested and validated in a laboratory setting. In the following sections, an overview of the design choices made is given, as well as the verification procedures utilized to ensure the SHS fulfills its requirements.

2. DESCRIPTION OF THE SAMPLE HANDLING SYSTEM

The SHS's main functionality is to receive between 50 cm^3 and 100 cm^3 of coarse regolith from the lunar surface with grain sizes up to 5 mm. It prepares the sample for analysis with a surface planarity and roughness better than $\pm 200 \mu\text{m}$. This sample is continuously presented in front of the mass analyzer (MA) aperture for chemical analysis. The planarity requirement stems from the sample surface having to be within the focused region of the laser beam for laser ablation/ionization be able to take place.

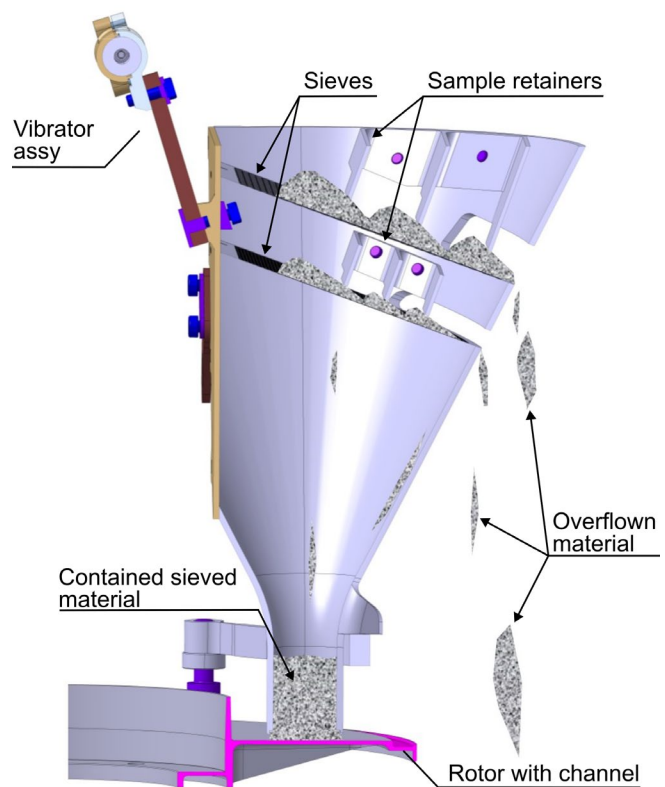


Figure 2: Graphic description of the funnel's principle of operation.

The lunar regolith is delivered via an external sample delivery system (SDS), which is part of the CLPS lander platform and thus out of scope of this instrument's design. The delivery system transfers the material into a drop-zone located above the funnel, which then collects and sieves the material as shown in Figure 2. The sieved material is dispensed onto a

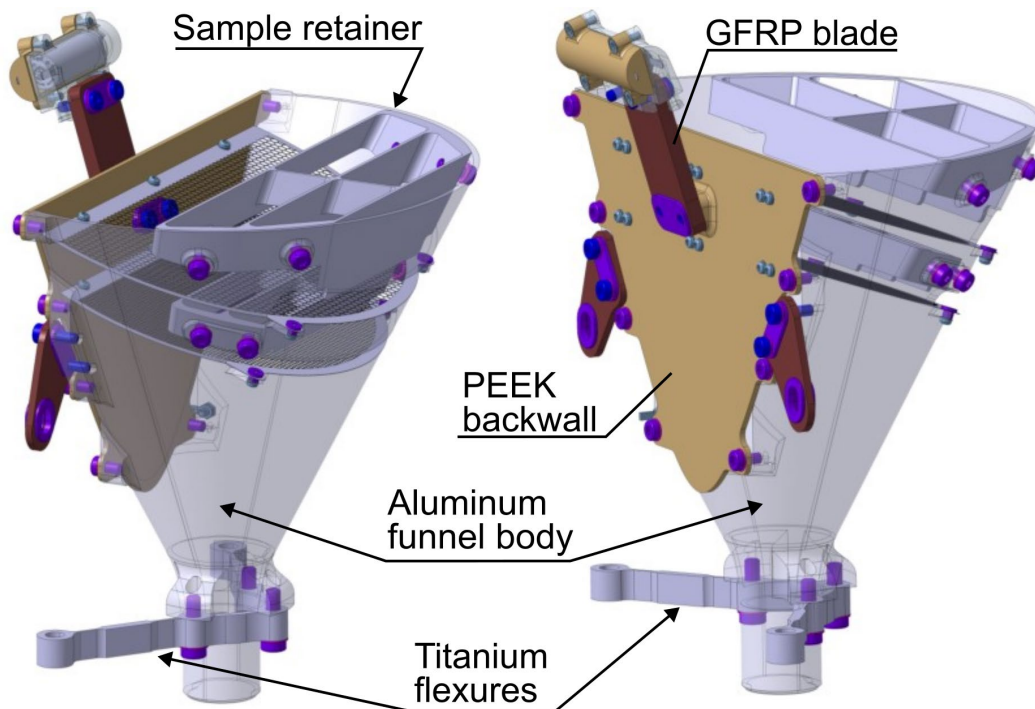


Figure 3: The current baseline funnel design of the CLPS-LIMS instrument.

rotating carousel which has an approximately 5 mm wide and 1.5 mm deep channel along its outer edge. A series of stainless-steel brushes push the material outwards into the channel and, in the process, completely fill the channel with the regolith sample. A skimmer compacts the sample and increases the surface quality before it is presented in front of the MA aperture. After analysis of the material, cleaning brushes remove the regolith from the carousel surface and empty the channel. The carousel rotates continuously during operation, continuously providing fresh sample material for chemical composition analysis.

The funnel, shown in Figure 3, with a large opening at the top is the interface for the CLPS provided SDS to dump the coarse sample material into. The funnel features two sieves that allow grains of 2 mm and 1 mm size, respectively, to pass towards the bottom of the funnel. Material which does not pass through the sieves falls out of openings on the side. These sieves are tilted at 20° to prevent stationary material clogging the funnel system. The tilt angle of the sieves allows for the lander to be tilted 10° relative to gravity vector in every direction without the material removal from the sieve surfaces being impeded. The sieves are made of woven metallic wires sandwiched in between metallic frames. Having woven wires should provide a degree of friction during launch and thus valuable dampening.

To facilitate sieving, a vibrator driven by a brushed DC motor (DCX10L Space; maxon Switzerland AG, Alpnach Dorf, Switzerland) is attached to the semi flexible, flat PEEK backwall of the funnel via a GFRP blade between the vibrator and funnel backwall. This is to amplify the deformation of

the backwall and thus the agitation of the attached sieves. Each sieving process will take approximately 1 minute. The cables used to operate the vibrator have a shielding, which is also used to thermally connect the motor with the thermally controlled monolith, to ensure that non-operational temperature range is respected. The whole funnel is attached with flexible suspensions, to limit parasitic vibrations originating from the vibrator spreading throughout the LIMS instrument and beyond. These interfaces have slits and allowances for shims, allowing moving the funnel up and down relative to the carousel before final integration.

A retainer structure (see Figure 3) is added above the first sieve. This is used to avoid excessive sample material being lost due to sliding off the sieve during coarse sample delivery. The retainer also decreases the flow of sample material off the sieve during sieving and thus maximizes the sample material usage efficiency.

The carousel employed in the SHS has been fabricated from titanium, a material with good stiffness-to-mass ratio. To further enhance this property and maintain structural integrity even under demanding conditions, internal support beams at the bottom of the carousel structure were incorporated into the design. For calibration purposes of the chemical composition analyses using LIMS, two reference samples are integrated along the carousel's circumference, thus splitting the sample channel into two parts and making a position reference system necessary. For this reason, a tactile switch is mounted to the bottom side of the carousel within a dust protected enclosure, which is actuated once every full rotation. As a stepper motor is used to rotate the carousel,

accurate positioning can be guaranteed after referencing the system once even with no additional encoders installed on the drive train, when respecting the motor's maximal stepping torque.

As the employed microchip laser system can potentially be damaged by direct back reflections from the carousel's surface, all surfaces that can be hit by the laser beam are tilted by 3° outwards. This ensures that any specular reflection from the carousel's surface is imaged outside of the laser by the optical system.

During launch and transit, unwanted carousel rotation is inhibited using a nD3PP-AL launch lock (DCUBED GmbH, Germering, Germany). It is disengaged after landing on the lunar surface.

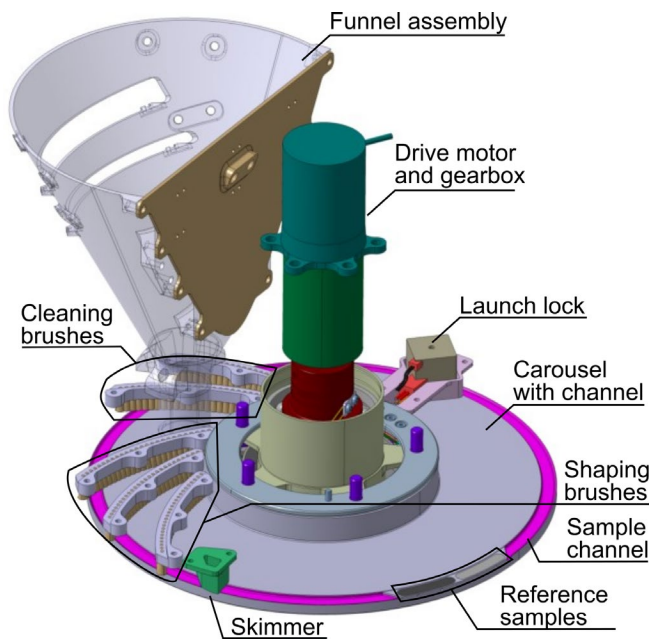


Figure 4: Overview of the SHS components. The vibrator structure is not shown in this figure.

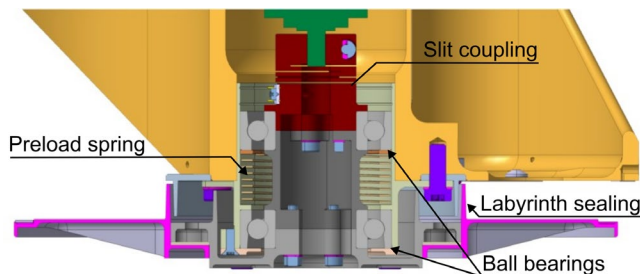


Figure 5: Close-up view on the SHS carousel drive train after the motor gearbox.

Drive train—A 2 phase stepper motor phySPACE 32-2-200-0,6-VGPL 32 (Phytron GmbH, Gröbenzell, Germany) with a matching 3-stage planetary gearbox are used to drive the carousel rotation. Space-application compatible Braycote (Castrol Ltd., Pangbourne, UK) lubricant is used to reduce friction and wear within. The gear has a high transmission ratio of 1:288 to maximize torque and position resolution per

motor step. The carousel's drive bearings are shielded from lunar regolith contamination using a labyrinth sealing system, as shown in Figure 5.

Considering the diameter of the carousel disc and the position resolution after the gear, a single step will result in sample movement relative to the mass analyzer of 10 µm per step, which approximately matches the diameter of the laser beam's focal spot. The nominal stepper motor speed is ~10 Hz which leads to a complete rotation approximately every 90 minutes if a continuous measurement campaign is conducted.

The output torque (at 70% of maximum motor current) of 7.2 Nm (guaranteed by supplier to be applicable over the whole temperature range) is four times larger than the torque peaks measured during laboratory test campaigns with lunar regolith simulant.

The output shaft of the gear has a polygon shape for robust coupling with the carousel. A slit coupling design has been chosen to connect the polygon shaped gear shaft with the carousel. It can compensate for axis misalignment in angle and account for relative movement along the axis. Relative movement perpendicular to the axis cannot be compensated, instead the gear and the carousel have a tight sliding fit in the monolithic structure. The coupling is made of gold-plated titanium. The carousel's rotational bearings are made of steel rings and are equipped with ceramic balls within a phenolic resin cage. The bearings' outer diameter of 47 mm has been chosen to be reasonably large to absorb moments that originate from the carousel during launch and regolith grains being potentially crushed by the skimmer. This moment reduction is aided by a wave spring which is pushing the outer rings of the bearing apart.

3. TESTING AND VERIFICATION OF THE SAMPLE HANDLING SYSTEM DESIGN

Extensive testing has been conducted with lunar regolith simulant, both to iteratively optimize the subcomponents of the SHS and finally validate the integrated design. Initial testing and optimization were performed separately for the funnel and carousel subassembly. The following sections describe the procedures employed and how the results from the test influenced the system design.

The experiments were conducted using lunar regolith simulant from the LHS (i.e. lunar highland simulant) series (Space Resource Technologies, Oviedo, FL, USA) in engineering quality. Depending on the campaign, LHS-1E with grain sized up to 1 mm or custom LHS-2E with grain sizes extended up to 5 mm were used. The composition and structure of regolith at the lunar south pole landing site is expected to exhibit similar properties as the highland regolith [19]. Thus, this simulant is deemed a suitable proxy material for the conducted tests. The regolith simulant material was baked out at 110°C for 24 h, as humidity influences the geomechanical properties. The baked-out material was stored in a desiccator under vacuum until usage. While conducting

the tests, the material was exposed to a non-humidity-controlled environment. After a day of testing, the material was baked out again.

Testing and Verification of the funnel

Ensuring efficient and reliable sample transport from the funnel to the SHS carousel is crucial for successful operation. This process starts with the sample material being dropped by the SDS onto the first sieve. The material's path must remain unobstructed under diverse conditions such as the spacecraft being tilted due to uneven or sloped landing sites. To guarantee proper sample handling in all foreseeable scenarios, various factors affecting this process have been investigated:

- Geometry of the funnel body and nozzle
- Sieve angle as well as sieving efficiency
- Vibration motor positioning

Evaluation of funnel and nozzle geometries—To identify the most effective funnel design, a series of breadboards (BB) were built and evaluated. Each BB was fabricated using either polylactic acid (PLA) or polyvinyl butyral (PVB) via fused filament 3D printing. Initially, simplified funnel shapes (geometry breadboards) were assessed to optimize material flow within the funnel (Figure 6). Funnel wall angles varied from 50° to 70° relative to the carousel plane, and for cylindrical designs, tube outlet diameters ranged from 12 mm to 24 mm. For the slotted funnel design, a slot width of 12 mm was tested.

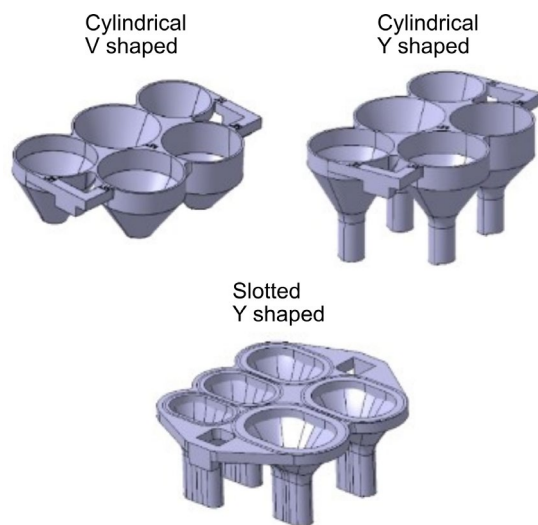


Figure 6: Overview of funnel geometries tested using the 3D printed breadboards.

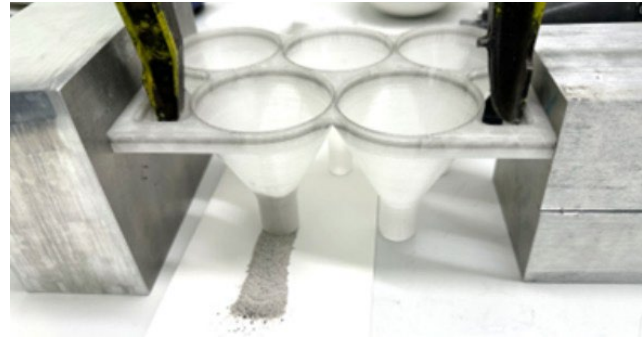


Figure 7: Test setup consisting of a series of 3D printed cylindrical Y funnel geometry breadboards. PVB was chosen as material as the surface quality can be improved by immersing it in isopropanol. The paper sheet was pulled continuously to simulate the carousel movement.

To assess the regolith outflow, the printed geometry BBs were fixed to aluminum blocks, maintaining a precise distance to the laboratory table. A sheet underneath the funnel nozzle mimics the movement of the carousel. After filling the funnel with regolith simulant, the sheet underneath is moved towards the front as shown in Figure 7, allowing the material to flow out of the funnel. The mass of dispensed material and the distance over which this happened, was measured to approximate the outflow rate.

The material behavior and the outflow rates of the different geometry types were measured and compared. For all following tests, LHS-1 regolith simulant was used. The outflow rate was defined as mass disposed per mm distance on carousel circumference.

Funnel designs with smaller tube diameters and smaller funnel angles often exhibit ratholing [20]. Ratholing refers to a condition where material flows only in a narrow central region of the funnel, while the surrounding material remains stationary and self-supporting. Despite ratholing, the material flow at the nozzle of the funnel can remain stable, as the surrounding material may collapse inward before any non-continuous funnel outflow occurs. At steeper funnel angles or larger tube diameters, ratholing becomes less likely, leading to the desired funnel flow behavior where some material is stagnant at the funnel wall while a larger volume flows simultaneously. Specifically, at a 70° funnel wall angle, continuous mass flow occurs across all diameters. In general, larger tube diameters and steeper funnel angles result in improved material flow through the funnel.

Many cylindrical V shaped funnels show bridging. The material does not create a hole in the middle of the funnel but supports itself and does not flow out. These phenomena can be seen with an outlet diameter of 12 mm at all funnel angles. Even the 50° and 55° funnel wall angles and 18 mm outlet diameter funnels show bridging. Generally, the V shaped funnels are problematic due to this phenomenon.

The material flow within the slotted funnel is promising, with mass flow occurring even at a 50° funnel wall angle,

indicating that bridging or ratholing is highly unlikely. However, a challenge arises from the elongated outlet hole, where friction is created by jammed particles between the long edge and the sheet below. Consequently, testing was omitted for the 18 mm and 24 mm slot width concepts due to this issue. Outflow rates of the slotted 12 mm geometry BBs are comparable to the cylindrical Y shaped BB with 12 mm nozzle diameter, as the opening of both nozzles are similar. The friction effect was absent in the earlier cylindrical geometry tests since they lack the extended edge. Overall, the slotted design concept is deemed less favorable due to the particle jamming at the outlet, leading to torque peaks in the powertrain.

All funnel geometry breadboards were fabricated with two different outflow nozzle configurations, as shown in Figure 8. The variant with a flat opening requires a clearance of 1.5 – 2 mm to the carousel surface to allow for all expected grain sizes to be able to exit the nozzle. For the nozzle variant with the enlarged opening, the side on which material outflow is expected, is enlarged by 1.5 mm in the vertical direction. This enlarged opening allows larger grains to exit the funnel while maintaining a small clearance relative to the carousel. Thus, preventing material from spilling out on the sides of the nozzle and producing a clearly defined outflow geometry on the carousel.

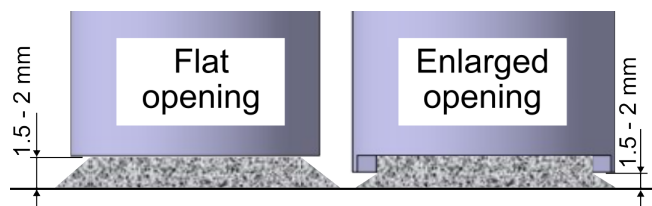


Figure 8: The two different nozzle configurations tested. The enlarged opening allows large grains to exit while reducing material spillage on the sides.

A cylindrical Y shaped funnel with a large tube outlet and a steep funnel angle emerged as the most promising geometry for optimal flow behavior within the funnel and efficient material outflow. This configuration facilitates a continuous material outflow without the need for vibration during carousel movement. The outflow rates rise with larger tube diameters, which reduces the carousel efficiency, as the sample channel in the carousel can be filled with a fraction of the incoming material. This challenge can be mitigated by positioning the funnel closer to the center of the carousel.

To validate the funnel behavior within a lunar gravity environment, the outflow tests were repeated with cork powder instead of lunar regolith simulant. The cork powder had a comparable grain size distribution and less than 1/6 the density of regolith simulant. The observed funnel outflow rate of the cork is comparable to the regolith simulant. No issues with ratholing or bridging were observed.

Evaluation of a complete funnel concept—Two funnel concepts were considered promising and designed in detail. The two concepts are subject to a tradeoff regarding outflow

rate, funnel opening and available space. Both concepts have a flat back wall at the SMU monolith side and two 12° declining sieves. An Ø 18 mm nozzle was determined to be a good compromise between outflow rate and material flow continuity. The monolithic SMU design allows the funnel to move closer to the carousel center and thus keep the amount of dispensed material per carousel revolution constant while enlarging the nozzle diameter. The maximum funnel angle is limited by the minimum required drop zone surface for the SDS delivering the sample material and the required sieve area. The two concepts have maximum funnel wall angles of 63° and 70°, respectively. As a 70° funnel would create a too small drop zone (with the given height and the flat back wall), the available drop zone was therefore extended by having a smaller 55° angle (only in one direction) in the top section of the funnel (asymmetric design). The effective drop zone size is slightly larger than the required 80 mm x 80 mm. For the second concept, to avoid multiple funnel angles within one design, the overall funnel angle was reduced to 63° (symmetric design). This allows to have a sufficiently large opening at the top and sieve sizes within the available interior volume. The drop zone is comparable to the previous concept but is wider on the sides.

Both concepts were produced by additive manufacturing (3D printing) and equipped with representative sieves. The 63° model is shown in Figure 9. The vibrator was attached horizontally and vertically on the back wall and on the funnel side. For both funnels, attaching the motor on the side of the funnel led to almost no sieving, independent of the motor axis orientation and motor speed. The relatively stiff, round part of the funnel does not excite the sieves and thus no sieving occurs. Attaching the motor to the backwall led to adequate sieving results for the symmetric funnel. The same configuration on the asymmetric funnel did not work well and sieving took considerably longer. The vertical (parallel to funnel axis) attachment of the vibrator did not lead to efficient sieving results for both concepts. Tests have shown that the funnel backwall and the motor bracket will be excited by the vibrator at a specific eigenfrequency. This excitement leads to enhanced sieving results. The asymmetric funnel has a much smaller and hence stiffer backwall which reduces this excitement. To prove this theory, a much stiffer backwall (8 mm instead of 1.5 mm) was added to the symmetric BB. This stiffened backwall made the sieving impossible. A thin backwall is therefore required to have efficient sieving. As the flight-quality funnel will be manufactured out of aluminum, a more flexible material is needed for the backwall. The current baseline foresees PEEK as backwall material.

The tested BBs did differ in overall stiffness from the planned aluminum funnel. To detect potential problems due to this mismatch, a more representative BB regarding stiffness was printed with a 5 mm thick funnel body and a 1.5 mm thin backwall. This new BB showed comparable sieving results to the symmetric BB despite more representative stiffness.

A sieve angle of 12° is beneficial for efficiency as the lateral material outflow is moderate. An uneven landing site scenario might reduce this sieve angle to 2° , which is insufficient, as larger grains would remain stationary on the sieves. Therefore, a larger nominal angle of at least 20° is foreseen. The asymmetric funnel concept is not being pursued further due to limitations in sieving efficiency and the complicated manufacturing.



Figure 9: 3D printed funnel with 63° wall angle used to test and validate the sieving performance.

Optimization of the vibrator efficiency—The design of the funnel backwall and motor connection is important for efficient sieving. A main limitation of the previous funnel tests is the aluminum bracket used to mount the vibrator to the funnel. During vibration, motor and bracket are excited together which influences the system.

The aluminum bracket was replaced by lighter, 3D printed parts. Clamping the motor between two printed shells and bolting the assembly directly to the funnel backwall did not lead to efficient sieving results, independent of the vibrator frequency. The excentric forces are too small to excite the backwall efficiently. When adding a blade between motor shell and backwall, the sieving was very efficient, and comparable to the results with the aluminum motor bracket. The vibration motor mounted on a blade can be simplified as a damped harmonic oscillator. With the blade- and backwall thickness the eigenfrequency of the system can be tuned. A stroboscope was used to visualize the eigenmode of the system. A blade that is too thin leads to an unwanted torsion mode. By using a thicker blade, a bending mode can be achieved. For the flight design, the printed blade material will be replaced by glass fiber laminate.

Sample material retainers—Previous tests have shown that a significant percentage of material is ejected laterally out of the funnel, which otherwise would have been small enough to pass through the sieves. Especially when pouring a large scoop into the funnel, some material instantaneously flows out of the funnel at the first sieve. The material that does not exit laterally or falls onto the second sieve immediately, creates a cone, with an angle of repose between 43.1° to 45.8° , as given by the LHS-2 material specifications. At some point, the cone extends all the way to the end of the upper

sieve. If more material is poured into the funnel, most of the additional material is ejected out of the funnel without having had the opportunity to be sieved. Laboratory tests have shown that the absolute amount of material passing the sieves, and therefore ending up inside the funnel, is mostly independent of the scoop size. Thus, the material usage efficiency of the overall system gets worse for large scoops. Two different countermeasures have been tested to increase the sample usage efficiency. In the first concept, the upper sieve was equipped with pillars which should prevent the material from outflowing, as shown in panel A of Figure 10. Alternatively, the second concept has blade shaped material retainers attached to the round section of the funnel, which are not in direct contact with the sieve (Figure 10, panel B). The pillar concept did not lead to a measurable efficiency increase. However, the blade concept increases efficiency. When pouring a large scoop into the funnel almost no material is ejected immediately. The clearance between sieves and retainers is critical and must be optimized to allow large grains to exit the funnel. When pouring a large scoop (118 g) into the funnel, these retainers lead to up to 10 g of additional material in the funnel. With this improvement, the sieving takes slightly longer as material remains longer on the sieves.

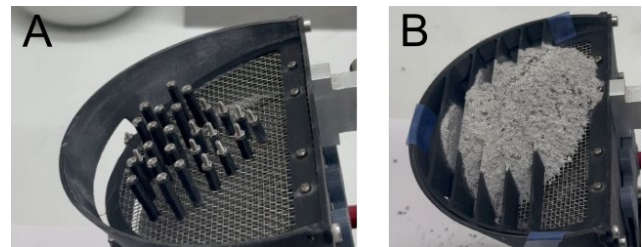


Figure 10: Sample retainer concepts based on pillar structures attached to the sieves (A) and blades attached to the funnel body (B).

Overall funnel efficiency—The amount of material passing the sieves mainly defines how much material can be analyzed by the mass analyzer. Small and large scoops (50 cm^3 and 100 cm^3) of LHS-2 extended up to 5 mm grain size were poured into the 3D printed, stiffness representative funnel with the blade vibrator to measure the efficiency of the optimized system. The whole funnel was tilted by 8° to reach a sieve angle of 20° as the BB is equipped with the 12° sieves. For these efficiency measurements, a retainer concept with three blades was used above the first sieve. A precise measurement of the sieving efficiency is challenging as many factors play a role, e.g. the position where the scoop is poured, the pouring height, the vibrator settings, etc. The total amount of material ending up in the funnel varied especially for large scoops. Six measurements with equal configuration led to results shown in Table 1. The overall efficiency for small scoops is higher than for large scoops. Some material does not reach the sieves themselves, when a lot of material is present, but rather floats on the material that is still present on the sieves. This is especially noticeable on the second sieve. This limits the efficiency for large scoops. Most material is now lost on the second sieve. Introducing the retainers also on the second sieve might lead to a slight

improvement. The additional complexity of this second retainer is currently deemed unnecessary, thus no second retainer is foreseen for the flight design.

Table 1: Determined sieving efficiencies for the optimized funnel design.

Scoop mass	Average material in funnel (range)	Efficiency
61 g (small scoop)	29.4 g (29 g – 31 g)	47 %
118 g (large scoop)	42 g (34 g – 49 g)	35 %

Verification of the carousel's functionality

The design verification for the funnel and brushes cannot be measured but are visually analyzed. Excessive material accumulation before brushes and inefficient channel cleaning has to be avoided. Various configurations were tested to find optimal parameters for the design.

The brush angle with respect to the radial direction can be changed from 10° to 50° on the BB. This influences how efficiently the dispensed material is pushed outwards towards the channel. Small angles lead to slow radial material flow. Hence, material accumulates before the brush. An unfavorable tilt of the carousel, as can be the result of the landing on the lunar surface, can even increase the material accumulation. A large brush angle increases the material outflow but requires longer brushes or even curved brushes. At 40° to 45° brush angles, sufficient material outflow was achieved, and no significant material accumulation was observed. The distance between carousel and brush (brush height) influences the amount of material that will be pushed outwards. To ensure that material accumulation before a single brush is acceptable and no material spills over the side of the brush, a sequence of three brushes with decreasing brush height is implemented on the SHS. The sequence of brush heights, which created similar material ejection volume at each brush, is 0.7 mm, 0.5 mm and 0.4 mm.

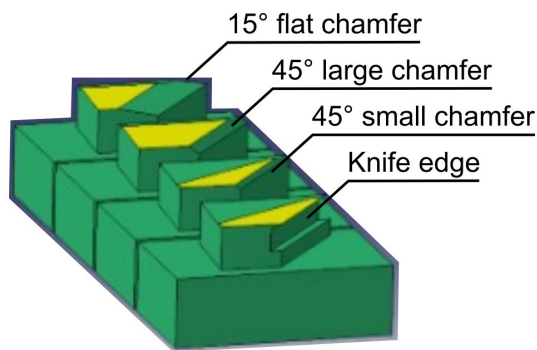


Figure 11: Various skimmer geometries that were tested on the SHS BB to ensure good sample compaction and planarity. Best results were obtained with the 15° flat chamfer skimmer, which ensure a flat sample surface and sample compaction.

Various skimmer geometries as shown in Figure 11 were tested. The three chamfered skimmers compact the sample and simultaneously eject excess material, whereas the knife

edge skimmer rather cuts excessive material without sample compaction and pushes it off the carousel. Due to the brushes which already pre-shape the sample material, relatively little material must be removed by the skimmer. With a 45° angle between skimmer edge and a radial line passing through the skimmer, sufficient material flow was observed. As a compacted sample is beneficial for LIMS measurements, the knife edge skimmer is not considered for all further planarity measurements.

The cleaning brushes remove material from the carousel and from within the sample channel. Tests have shown that two brushes are required to sufficiently clean the carousel. One flat brush cleans the carousel surface (with 0.1 mm clearance). The second brush cleans the channel and the remaining particles on the carousel surface. The second brush is manufactured with a step to reach to the bottom of the channel. Some material remains in the channel, but this material is covered with pristine regolith material during the next sample delivery. Therefore, the channel must not be completely empty. For both brushes, the same angle (45°) can be used as for the shaping brushes.

Generally, the empirically determined settings with a 45° brush angle, skimmer and two cleaning brushes work well on the SHS BB. A test with 699 g of LHS-1 processed by the carousel was executed to simulate a complete lifetime. The amount equals 20 small scoops or 10 large scoops with an estimated funnel efficiency of 50%. The test showed no clogging or degradation on the brushes and the skimmer. All excessive material was removed, and no long-time material accumulation was detected.

Sample planarity and roughness verification

Sample planarity and roughness strongly affects the quality of obtainable mass spectra by the LIMS instrument. As such, a method to quantify and compare sample surface qualities prepared by the SHS breadboard system is needed. Several constraints and requirements had to be considered when designing the measurement system. For one, the loose nature of the sample material excluded tactile techniques and necessitated the use of optical profilometry techniques to determine the sample surface quality. As the profilometer had to be integrated into the SHS breadboard, the system had to be compact enough to fit onto the breadboard. Additionally, the profilometer's instantaneous field of view (FOV) should cover the width of the sample channel (~5 mm), to avoid the need for scanning movements and thus speed up the measurement.

A system based on focus variation microscopy was devised as it fulfilled all the constraints and was technically and cost-effectively realizable.

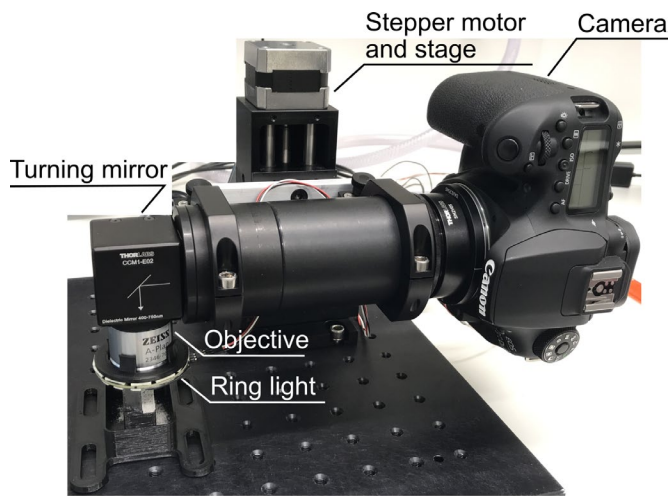


Figure 12: The microscope setup developed to measure the sample planarity as prepared by the SHS breadboard.

The principle of operation consists of taking a sequence of pictures with a shallow depth of field of the sample surface at different distances from the nominal sample surface. During data processing, regions of the images which are in focus at the respective distance are detected. This allows to construct a 3D profile of the imaged surface. The optical design is based on a Canon 90D DSLR camera featuring a large APS-C sensor (22.3 mm x 14.9 mm) compared to commercially available industrial vision cameras. This sensor size made it possible to comfortably design the microscope optics to accommodate for the large FOV with the required shallow depth of field. The imaging system of the microscope consists of 2.5x achromatic microscope objective (A-Plan 2.5x/NA 0.06, Carl Zeiss AG) and a corresponding 1x tube lens (164.50 mm FL, No. 425308-0000-000, Carl Zeiss AG). For illumination of the sample surface, a ring light consisting of 16 RGBW LEDs (NeoPixel Ring 2855, Adafruit Industries LLC) was attached through a 3D printed mounting assembly directly to the objective. The assembled microscope was mounted to a motorized vertical stage driven by a bipolar NEMA17 stepper motor with 200 steps per revolution, as shown in Figure 12. By driving the motor in full-step mode, a vertical resolution of minimally 2.5 μm between focus planes was realized. The stepper motor and the ring light were controlled using a microcontroller (Arduino UNO SMD, Arduino S.r.l.) combined with an H-bridge driver (Motor Shield 1438, Adafruit Industries LLC). The microcontroller receives commands from a controlling computer to initiate a certain vertical movement. Additionally, the DSLR camera was also connected to the computer and could be remote operated using the gPhoto2¹ software package. This allowed for fully automated recording of the image sequences.

Data analysis was performed using a custom MATLAB script. Using the externally developed *fstack* function², the respective in-focus pixels from each image in the focus stack could be extracted. A curvature correction using a 3rd degree

polynomial function was performed on the height map to accommodate for the microscope not being perfectly perpendicular to the sample surface. The sample planarity can be extracted as the relative number of pixels within a predefined height range.

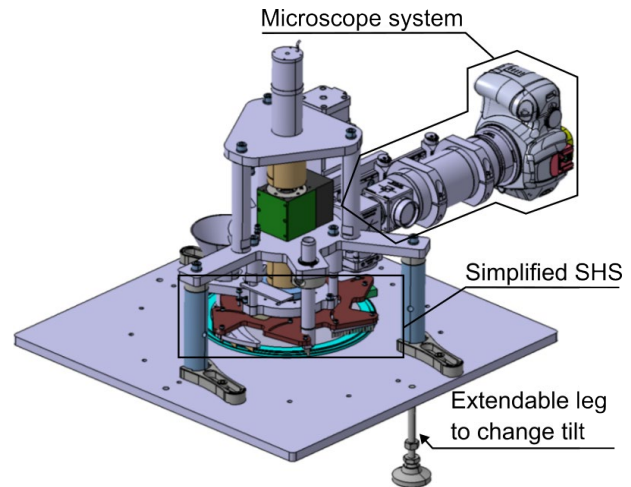


Figure 13: SHS BB setup with the integrated microscope for sample planarity measurements. The microscope can be positioned using a manual translation stage such that the objective is above the sample channel.

With the microscope system integrated into the SHS BB setup, the sample surface quality could be monitored over long periods of operation without user interaction. Analysis of the obtained image sequences resulted in distributions depicting the number of pixels in focus at a certain offset from the nominal surface height. Such a distribution for a reference sample can be seen in Figure 13. This sample was prepared manually in an equivalent fashion to samples which were measured by mass spectrometry and found to lead to acceptable results. Thus, a sample surface planarity of $\pm 200 \mu\text{m}$ is deemed acceptable, as described in [17] as well. As comparison a sample with poor surface quality is shown in Figure 14. The large central hole is clearly visible in the 3D profile as well as in the broader depth distribution.

Surface planarity of the sample can mainly be influenced with the skimmer geometry. The two 45° chamfered skimmers (Figure 11) do not differ strongly and are expected to generate comparable planarity results, whereas the 15° chamfered skimmer is expected to behave differently regarding achievable planarity and roughness.

¹ <http://www.gphoto.com>

² <https://github.com/joe-of-all-trades/fstack>

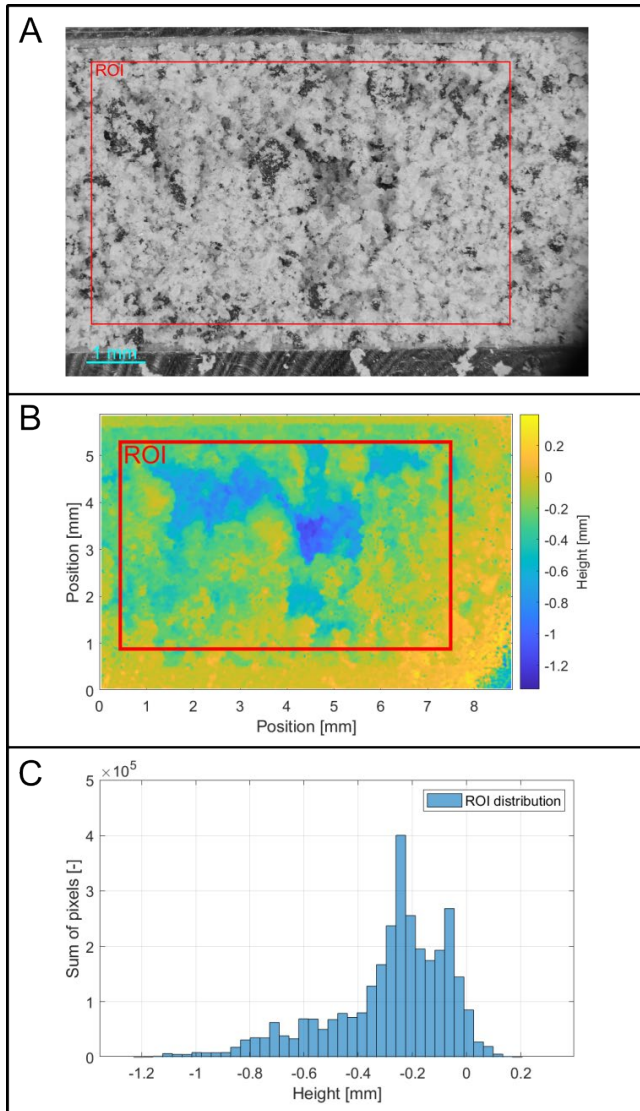


Figure 14: An example of a sample with poor sample surface quality as measured by the microscope setup. Panel A shows the focus-stacked composite image, for which the height profile is shown in panel B. The hole in the center of the region of interest (ROI) causes a wide sample height distribution (Panel C), and thus classified as poor sample surface quality.

Each skimmer was tested using an identical measurement procedure. The recorded image stacks consisted of 31 individual focus layers with step sizes of 75 μm , resulting in a total movement of 2.25 mm. During 1.5 carousel revolutions, a total of 160 height distributions were recorded. Brush heights and orientations are set to the previously optimized values. As sample material LHS-1 with a grain size distribution up to 1 mm was used.

The planarity measurement was started after a first initial rotation of 225° (~375 mm distance along the circumference), allowing for the channel to fill up with regolith simulant. After additional 25° (~40 mm distance) of rotation, the surface quality starts to rise, as can be seen in Figure 15. At this point, the filled part of the channel reaches

the microscope. Rotating the carousel 25° further, the planarity is reaching a steady state. Clear differences between the 45° skimmers to the 15° skimmer are noticeable. The 15° skimmer prepared an average of 99% of the sample material with height variations less than the required $\pm 200 \mu\text{m}$. For the sample material prepared by the 45° skimmers only 95% of the analyzed area lies within the requirements.

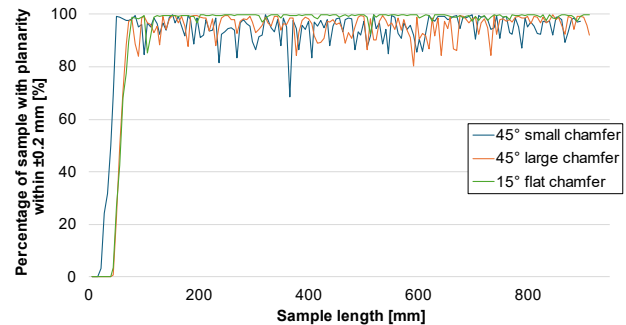


Figure 15: Measured percentage of the sample generated by different skimmer geometries that lie within the requirements.

Additionally, to the different skimmer geometries, the influence of potentially larger grain sizes on the sample height distribution was investigated. This is relevant since our tests revealed the possibility of elongated regolith particles with one dimension larger than the smallest sieve size (1 mm), to fall. For this purpose, the well-performing 15° skimmer was used to prepare a sample using LHS-2 regolith simulant, which was sieved with the funnel BB. A comparison of the results obtained with LHS-1 and sieved LHS-2 are shown in Figure 16. The average number of measured height profiles with a planarity within requirements decreased by 2% to 97% for the sieved LHS-2. In general, we observed that larger grains led to difficulties while preparing the sample. The larger grains preferentially get stuck in the carousel structures and cause grooves and holes within the sample surface, if they are pulled along as the carousel rotates.

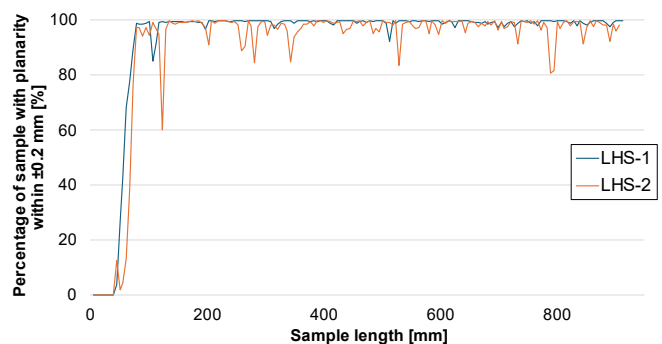


Figure 16: Planarity comparison between simulants of different maximum grain sizes.

As the sample preparation must work reliably even with lander tilts up 10°, planarity measurements were performed with the SHS BB being tilted 10° and 20°. At 10° tilt, the

material flow on the carousel does not differ from the flat (0° tilt) tests. No material accumulation before brushes could be detected. At 20° inclination, a slight accumulation before the first shaping brush was observed. The material must be pushed upwards against gravity, which hinders the material outflow. It should be noted that this effect depends on the tilt direction. Performed planarity measurements, in both configurations using the 15° skimmer, showed no noticeable difference to the measurements performed with a flat SHS BB.

4. SUMMARY

In this contribution we present the challenges encountered while designing a Laser Ablation Ionization Mass Spectrometer (LIMS) to be launched on a CLPS mission to the lunar south pole for the *in-situ* chemical analysis of lunar regolith. Extensive design changes had to be carried out compared to our previous publications [16], [17], to ensure strict compliance with mechanical launch loads as described by NASA's GEVS. This required the introduction of a monolithic main support structure fabricated from AlBeMet AM162 to ensure high stiffness and thus low load amplifications at the subassemblies.

The instrument's sample handling system (SHS) has been extensively optimized, tested and validated using lunar regolith simulant. The tests performed with different funnel geometries led to optimized designs for all funnel elements such as funnel angle, funnel nozzle geometry and sieve vibrator mounting. The funnel geometry must be carefully chosen to avoid clogging effects, such as ratholing or bridging, and has to take into account the mechanical properties of the sample material, with the overall goal to increase the scientific return of the mission.

For the SHS carousel an efficient configuration of brushes and skimmers was found. This makes preparation of a planar sample surface possible, as it is required for stable laser ablation conditions using LIMS. The overall system has been tested and validated for lander tilts up to 10°.

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REFERENCES

- [1] "Artemis III Science Definition Team Report," NASA, NASA/SP-20205009602, 2020. Accessed: Sep. 27, 2024. [Online]. Available: <https://www.lpi.usra.edu/lunar/strategies/resources/Artemis-III-Science-Definition-Team-Report-2020.pdf>
- [2] J. Gross and K. H. Joy, "Evolution, Lunar: From Magma Ocean to Crust Formation," in *Encyclopedia of Lunar Science*, B. Cudnik, Ed., Cham: Springer International Publishing, 2016, pp. 1–20. doi: 10.1007/978-3-319-05546-6_39-1.
- [3] G. Heiken, D. Vaniman, and B. M. French, Eds., *Lunar sourcebook: a user's guide to the moon*. Cambridge [England]; New York: Cambridge University Press, 1991.
- [4] K. H. Joy *et al.*, "Direct Detection of Projectile Relics from the End of the Lunar Basin-Forming Epoch," *Science*, vol. 336, no. 6087, pp. 1426–1429, Jun. 2012, doi: 10.1126/science.1219633.
- [5] K. H. Joy, I. A. Crawford, N. M. Curran, M. Zolensky, A. F. Fagan, and D. A. Kring, "The Moon: An Archive of Small Body Migration in the Solar System," *Earth Moon Planets*, vol. 118, no. 2–3, pp. 133–158, Nov. 2016, doi: 10.1007/s11038-016-9495-0.
- [6] K. H. Joy *et al.*, "The isotopic composition of volatiles in the unique Bench Crater carbonaceous chondrite impactor found in the Apollo 12 regolith," *Earth and Planetary Science Letters*, vol. 540, p. 116265, Jun. 2020, doi: 10.1016/j.epsl.2020.116265.
- [7] A. A. Nemchin, R. T. Pidgeon, M. J. Whitehouse, J. P. Vaughan, and C. Meyer, "SIMS U–Pb study of zircon from Apollo 14 and 17 breccias: Implications for the evolution of lunar KREEP," *Geochimica et Cosmochimica Acta*, vol. 72, no. 2, pp. 668–689, Jan. 2008, doi: 10.1016/j.gca.2007.11.009.
- [8] M. Anand *et al.*, "A brief review of chemical and mineralogical resources on the Moon and likely initial in situ resource utilization (ISRU) applications," *Planetary and Space Science*, vol. 74, no. 1, pp. 42–48, Dec. 2012, doi: 10.1016/j.pss.2012.08.012.
- [9] G. Cesaretti, E. Dini, X. De Kestelier, V. Colla, and L. Pambaguian, "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology," *Acta Astronautica*, vol. 93, pp. 430–450, Jan. 2014, doi: 10.1016/j.actaastro.2013.07.034.
- [10] N. Leach, "3D Printing in Space," *Architectural Design*, vol. 84, no. 6, pp. 108–113, Nov. 2014, doi: 10.1002/ad.1840.
- [11] A. Meurisse, A. Makaya, C. Willsch, and M. Sperl, "Solar 3D printing of lunar regolith," *Acta Astronautica*, vol. 152, pp. 800–810, Nov. 2018, doi: 10.1016/j.actaastro.2018.06.063.
- [12] P. Wurz, M. Tulej, A. Riedo, V. Grimaudo, R. Lukmanov, and N. Thomas, "Investigation of the Surface Composition by Laser Ablation/Ionization Mass Spectrometry," in *2021 IEEE Aerospace Conference (50100)*, Big Sky, MT, USA: IEEE, Mar. 2021, pp. 1–15. doi: 10.1109/AERO50100.2021.9438486.
- [13] U. Rohner, J. A. Whitby, and P. Wurz, "A miniature laser ablation time-of-flight mass spectrometer for *in situ* planetary exploration," *Meas. Sci. Technol.*, vol. 14, no. 12, pp. 2159–2164, Dec. 2003, doi: 10.1088/0957-0233/14/12/017.
- [14] U. Rohner, J. A. Whitby, P. Wurz, and S. Barabash, "Highly miniaturized laser ablation time-of-flight mass spectrometer for a planetary rover," *Review of Scientific Instruments*, vol. 75, no. 5, pp. 1314–1322, May 2004, doi: 10.1063/1.1711152.
- [15] A. Riedo, A. Bieler, M. Neuland, M. Tulej, and P. Wurz,

“Performance evaluation of a miniature laser ablation time-of-flight mass spectrometer designed for *in situ* investigations in planetary space research: Miniaturised laser ablation tof mass spectrometer,” *J. Mass Spectrom.*, vol. 48, no. 1, pp. 1–15, Jan. 2013, doi: 10.1002/jms.3104.

- [16] P. Wurz *et al.*, “In Situ Lunar Regolith Analysis by Laser-Based Mass Spectrometry,” in *2023 IEEE Aerospace Conference*, Big Sky, MT, USA: IEEE, Mar. 2023, pp. 1–10. doi: 10.1109/AERO55745.2023.10115714.
- [17] P. Keresztes Schmidt *et al.*, “Sample handling concept for in-situ lunar regolith analysis by laser-based mass spectrometry,” in *2024 IEEE Aerospace Conference*, Big Sky, MT, USA: IEEE, Mar. 2024, pp. 1–10. doi: 10.1109/AERO58975.2024.10521190.
- [18] *General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects*, GSFC-STD-7000, Greenbelt, MD 20771., Apr. 28, 2021. [Online]. Available: https://standards.nasa.gov/sites/default/files/standards/GSFC/B/0/gsfc-std-7000b_signature_cycle_04_28_2021_fixed_links.pdf
- [19] P. D. Spudis, B. Bussey, J. Plescia, J.-L. Josset, and S. Beauvivre, “Geology of Shackleton Crater and the south pole of the Moon,” *Geophys. Res. Lett.*, vol. 35, no. 14, p. L14201, Jul. 2008, doi: 10.1029/2008GL034468.
- [20] D. Schulze, *Powders and Bulk Solids: Behavior, Characterization, Storage and Flow*. Cham: Springer International Publishing, 2021. doi: 10.1007/978-3-030-76720-4.

BIOGRAPHY



Peter Keresztes Schmidt received his B.Sc. and M.Sc. in Chemistry at the ETH Zürich, Switzerland. He is currently working as a PhD student in Bern, Switzerland, where he is developing a new LIMS instrument for in-situ studies on the lunar surface.



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Peter Wurz has a degree in electronic engineering (1985), an M.Sc. and a Ph.D. in Physics from Technical University of Vienna, Austria (1990). He has been a post-doctoral researcher at Argonne National Laboratory, USA. Since 1992 at the University of Bern. He is Professor of physics, 2015–2022 head of the Space Science and Planetology division, and since 2022 director of the physics institute. He has been Co-I and PI for many science instruments for space missions of ESA, NASA, ISRO, CNSA, Roscosmos, and JAXA.