Preliminary Assessment of the Capabilities of a Novel Instrument for Particulate Matter Monitoring in Space Applications

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To ensure astronaut health as well as proper operation and integrity of spacecraft cabin systems, it is imperative to have reliable instruments for continuous air quality monitoring. To this end, the development of an innovative in-situ airborne particle monitoring instrument was initiated. The instrument uses light scattering measurements at multiple angles to retrieve particulate matter (PM) size distribution and concentration in an in-situ monitored volume. This technology does not require air sampling with pumps or ventilators, which complies with operations in vacuum or low-pressure environments like those of the lunar or Martian surface. Furthermore, its reduced footprint makes it attractive for use in the cluttered volume of spacecraft cabins. This paper presents the latest research activities carried out with the in-Situ Individual Particle Sizer (iSIPS) apparatus. It describes a host of experiments designed to ascertain its capability to meet key requirements for air quality monitoring in spacecraft. The tests aim to demonstrate the detection and measurement of the mass concentration for a selection of PM types (e.g., lunar regolith simulant, smoke residues, and dust generated by crew activities) with sizes up to 10 µm. In addition, early experimental work is presented to show the instrument ability to differentiate various PM types from mono-composition releases or from a mixture of two (2) types. At last, the paper discusses the potential addition of characterization modules (e.g., polarization, fluorescence) to enhance the instrument capabilities in discriminating the monitored particulate types in terms of composition and shape.

Acronyms and Nomenclature

AAC	=	Aerodynamic Aerosol Classifier
ARD	=	Arizona Road Dust
CPC	=	Condensation Particle Counter
CRS	=	Combustion Residue Simulant
ECLSS	=	Environmental Control and Life Support System
EVA	=	Extravehicular Activity
HLS	=	Human Landing System

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INO = Institut National d'Optique
iSIPS = in-Situ Individual Particle Sizer
LRS = Lunar Regolith Simulant
OPC = Optical Particle Counter
PLSS = Portable Life Support System
PM2.5 = Particulate Matter having an aerodynamic diameter of less than 2.5 μm
PM10 = Particulate Matter having an aerodynamic diameter of less than 10 μm
ROI = Region of Interest
UV = Ultraviolet

I. Introduction

A. Background/Context

PARTICULATE matter (PM), especially lunar regolith, can have detrimental health and safety issues on astronauts as they embark towards lunar voyages.[1,2,3] As evidenced by the Apollo missions, the presence of regolith in the cabin of the lunar module or in the command module induced respiratory, dermal, allergic, and ocular problems, some of which occurred during critical mission segments.[1,4] Besides these negative health impacts, peculiar characteristics of the lunar dust such as composition, morphology, and electrical charging capacity bring along problems of material abrasion (e.g., spacesuits, joints, gears) as well as stickiness onto surfaces (e.g., spacesuits, portable life support system (PLSS), optical lens). They can thus jeopardize proper operation and integrity of moving mechanical devices as well as of electric and optical systems (e.g., life support systems, spacesuit, PLSS, airlock, air revitalization, water recovery, thermal exchangers, antennas).[2,5,6] In addition to planetary regolith, particulate matter found in the cabin of spacecraft can be related to humans (skin flakes, hairs, personal hygiene products, fabrics, food, etc.) or to systems (exercise equipment, spacecraft hardware, etc.).[7,8] In a worst-case scenario, smoke related particles from a fire or pre-fire overheat event can also potentially occur in the cabin space.

In the context of deep space exploration, that of the Moon in particular, there is a need for the continuous monitoring of suspended particulate matter (e.g., regolith dust, smoke, aerosols) in the cabins of spacecraft (Orion shuttles, Human Landing System (HLS)) and rovers, in habitats (lunar base, Gateway) as well as in the vicinity of habitats and lunar infrastructures to ensure the health and safety of astronauts indoors or outdoors, to optimize operations on the surface (transport, exploration, mining, etc.), and to avoid or minimize equipment failures attributable to regolith effects.

The continuous monitoring of dust and particulate materials in suspension is relevant inside or outside spacecraft, habitats, and in airlocks. Multiple experimental and commercial devices use measurements of scattered light combining either multiple angles, wavelengths, and polarization or a combination of these into nephelometer instruments. These generally perform measurements of scattered light from multiple particles at the same time and thus lack the capability to discriminate characteristics of individual particles.[9,10] However, Optical Particle Counters (OPC) assess the particle size one at the time through continuous air samples flowing through a confined measurement volume. The air sample contains particles that interact with a collimated laser beam traversing the air flow. The size information is retrieved using the measurements of the scattered light at a certain angle, often at 90° where the phase function characteristics are advantageous in discriminating different sizes with a relative weak influence of light intensity. The measured particle sizes are then compiled over time and size classes to infer the particle size distribution.

Recently, an innovative monitoring approach for particles in suspension, called iSIPS (in Situ Individual Particle Sizer), has been developed by INO and presented in an earlier publication.[11] The patented approach[12] has a robust design with well suited characteristics for a wide range of applications. Its concept of operation allows the retrieval of size distribution and concentration for the particle population present within an interrogated volume. With the current development setup, it is estimated that the upper limit for particle concentration is about 100 μg/m^3 whereas the lower limit corresponds to the background aerosol concentration (less than 2 μg/m^3). Previous tests showed that the actual iSIPS configuration provides confident retrieval for aerosol sizes from 0.1 to 1.1 μm. Further tests are planned to estimate the retrieval accuracy and to evaluate appropriate designs that will allow expanding the size range.

The main advantage of iSIPS is that it does not need air sampling through pumping or ventilators and thus offers an elegant method to tackle the characterization of particles in suspension not only in a pressurized atmosphere but also in a vacuum (e.g., lunar or Martian surface). This capability allows for a single instrument to address air environments with various pressures such as those of air locks and various spacecraft (e.g., Orion, Gateway, HLS, rovers). With no mobile parts combined with maintenance routines limited to self-cleaning features, this technology

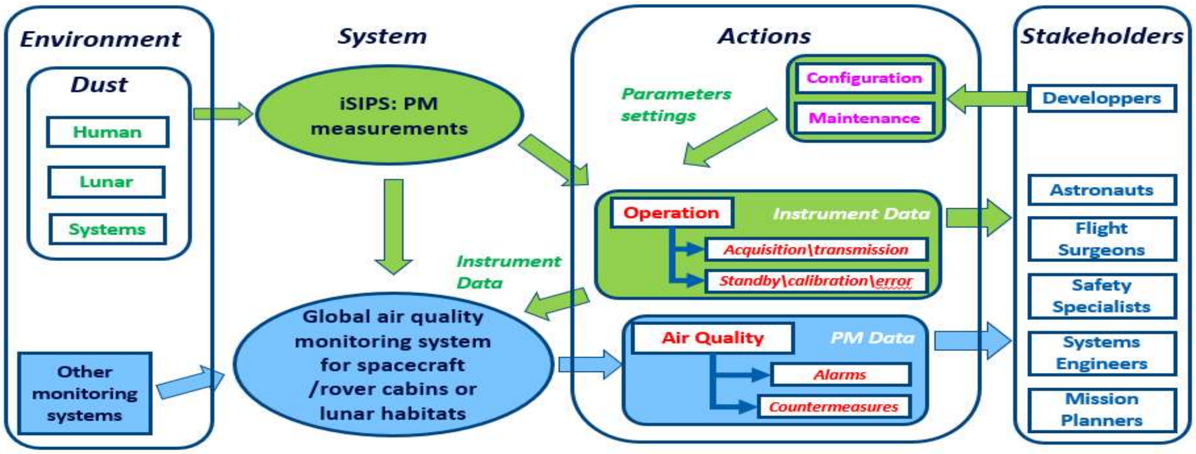

Figure 1. Schematic diagram of an iSIPS integrated ECLSS.

proves to be well adapted for space applications, where the requirements on maintenance and periodic calibrations are challenging. Also, its size, weight and power consumption offer a true potential towards miniaturization. All this makes iSIPS an attractive instrument to be deployed in air quality monitoring systems a well as in filtration devices or other air cleaning technologies.

B. Early Target Application

Although the instrument could eventually be used outside spacecraft or habitats, the currently targeted application is that of monitoring PM in the cabin of spacecraft, habitats or rovers. As shown in Figure 1, the PM monitoring device would be part of an integrated environmental control and life support system (ECLSS). The device would focus on real-time PM monitoring by detecting and measuring the PM mass and number concentration. By providing clues upon the origin of the PM (regolith, soot resulting from combustion, or others (e.g., human skin flakes, spacecraft systems residues), it could thus serve as a back-up fire (smoke) detector. iSIPS potentially offers to carry out size distribution measurements on PM without the need for air sampling.

C. Research Objectives

The current research aims to perform a preliminary assessment of the iSIPS technology performances with its current hardware and software state in terms of the aforementioned potential needs and requirements for monitoring particulate matter in the cabin of a spacecraft. This will in turn help to indicate paths towards improvements of the instrument hardware and processing software. The objectives are pursued in line with a thorough search in the open literature,[3,5] as well as discussions with experts in the field. This helped to sort out a number of requirements to be met by a PM monitoring device in a spacecraft or rover cabin or in a lunar habitat or orbital outpost. At first, the objective is to demonstrate the capability of iSIPS to detect and measure the size distribution of three (3) types of particulate matter: a reference terrestrial mineral PM, the Arizona Road Dust (ARD), a simulated lunar regolith, and residues from a fire, soot. It was originally planned to test PM samples from human origin or activities. However, it was not possible to find any suitable reference materials with a proper size distribution. It was originally planned to test PM samples resulting from human activity but available samples present size distributions superior to 50 µm, which are way above the targeted goals of this experiment. In addition, considering the early stage of this R&D project and the schedule constraints, commercially available combustion residues samples were procured although it is acknowledged that there are differences between these particles and either soot (fractal agglomerates of carbon) or smoke particles from thermal decomposition.

The second goal of the research is to understand the different signature of each PM type and to carry out a preliminary assessment of the capability of iSIPS in discriminating each type of PM in a mixture of two or three types of PM with either the same size distribution or with different size distributions. Following a search in the open literature,[3,5] the targeted requirements to assess in this study were summarized below:

- The system must measure a concentration of particulate matter by mass of a volume of a cabin or habitat interior.

- The system should be able to differentiate particulate matter coming from three (3) sources: lunar regolith dust, carbon black test particles (as a surrogate for some types of smoke), and dust generated by astronauts or cabin systems.
- The system must be able to operate despite significant variations in dust concentration.
- The system must measure the mass concentration (calibrated with standards) (mass per unit volume) of particulate matter whose effective diameter is between 0.02 µm and 2.5 µm.
- The system should measure the mass concentration (calibrated with standards) (mass per unit volume) of particulate matter whose effective diameter is between 2.5 µm and 10 µm.
- The system shall measure the mass concentration (calibrated with standards) (mass per unit volume) of particulate matter with an accuracy of <<35 $\mu g/m^3$ over 24 hours.
- The system shall give an alarm if the concentration equals or exceeds the permissible exposure limit (e.g., 0.3 mg/m^3).[3]
- The system should be able to differentiate respirable fractions of lunar dust and other particulate matter into ultrafine (<0.1 µm), fine (0.1–2.5 µm), and coarse (2.5–10 µm) particulates.
- The system should give an indication of the particle size distribution.
- The data acquisition rate must be at least 10 Hz during operational monitoring of air quality.
- The system must be calibrated, prior use, with reference instruments for different types of measurements.

This paper first describes the experimental setup, explains the working principle behind the iSIPS approach, details the experimental procedures and presents the preliminary data. The future work and the intended research path are outlined in the conclusion.

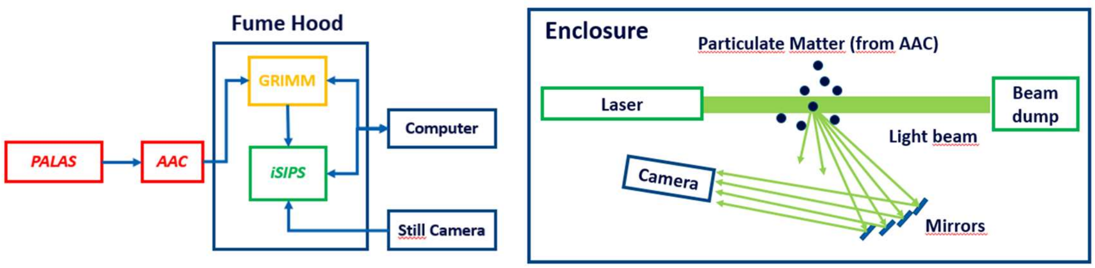

Figure 2. Schematic diagram of the experimental setup (left) and iSIPS instrument (right).

II. Setup and Experimental Procedures

A. Setup and Materials

The experimental setup diagram is presented in Figure 2, with the particle sizer iSIPS measuring the particulate samples generated by a solid particle disperser (Palas RBG 1000) and then size-selected by the aerodynamic aerosol classifier (AAC) (Cambustion). The aerosol size distribution is also provided by a calibrated portable dust monitor (GRIMM Series 1.100) that is used as a reference for size distribution measurements. The iSIPS and the GRIMM are located inside a polypropylene benchtop and free-standing ductless fume hood (Air Clean Systems). The measurement protocol is managed by a computer, used to drive and control both iSIPS and GRIMM data acquisition. An optical microscope is also used for visual analysis of particulate samples, before and after size classification by the AAC.

The iSIPS hardware comprises an optical breadboard (Figure 3) with the following optical components: a collimated laser diode source (532 nm, less then 50 mW, Whisper IT Free Space Series W532), a monochrome, 2.3 megapixels camera (acA1920-40gm Basler ace GigE) with a 6.67 mm aperture lens, and a set of four (4) first reflection surface mirrors. The data acquisition consists of a series of monochrome images, recorded by the acquisition control computer and further stored and processed off-line. The acquisition frame rate and exposure time can be adapted according to the aerosol sample concentration.

B. Calibration procedure

A calibration procedure is carried out regularly before any major test campaign. The procedure consists in verifying and adjusting the setup geometry, i.e. the relative positioning of the optical components, and its related effect on image rendering with respect to 3D positioning. Top-view images are used to assess the relative positions between the laser, mirrors, and camera using checkerboard grids. In addition, pictures taken with an inclined checkerboard target helps to determine the direction of beam propagation along the beam axis. The camera calibration is performed using the checkerboard target moved along the axis of the laser beam and imaged on the setup camera. This allows us to build corresponding look-up tables between the 3D positions given by checkerboard points and their 2D positions in the camera image as reflected by the four mirrors. These calibration tables ensure the framework of algorithm application for a precise positioning of the particle.

C. ISIPS Operation

Once the dust for a given type (single composition or multiple compositions) has been generated via the Palas and AAC instruments at a proper concentration and into the desired size range, the particulate matter is illuminated by a laser in a fixed and restricted volume (estimated at 25 mm of beam path). The laser light is scattered by the particles, with scattered angular pattern partially recovered by a series of mirrors and reflected towards the camera.

The processing technique is largely detailed elsewhere[11]. The recorded image contains each angular component of the scattered light for each particulate present in the interrogated volume as series of signal zones (pixel clusters) present in four regions of interest (ROI) corresponding to the 4 mirrors. The processing algorithm detects the clusters and matches the four clusters associated to the scattering pattern coming from the same particle. Using positioning information from the setup calibration procedure, the position of the particle is assessed in 3D space, which allows to determine the scattering angles with respect to the laser beam direction and mirror positions/orientations. The knowledge of the scattering angles is then combined with assumptions on scattering pattern simulations to retrieve the particle size. The processing is applied over all the clusters detected within the image and provides size information on all particles. The sample size distribution is obtained by cumulating the processing results over a series of image acquisitions with respect to the frame rate and time interval. The interrogated volume is estimated as the volume covered by the 3D positions of all detected particles. Note that the particles between the laser and the monitored volume will scatter the laser light beam and will reduce the laser beam intensity in the interrogation volume. This has no effect on the instrument processing procedure, as it is based on the intensity ratios rather than absolute intensities. Also, some particles from outside the interrogated volume might have scattering contributions recorded in the image ROIs. However, this is addressed by the algorithm, which will reject the particles positioned from outside the volume, or particles with partial contributions (i.e. particle image in only one or two ROIs).

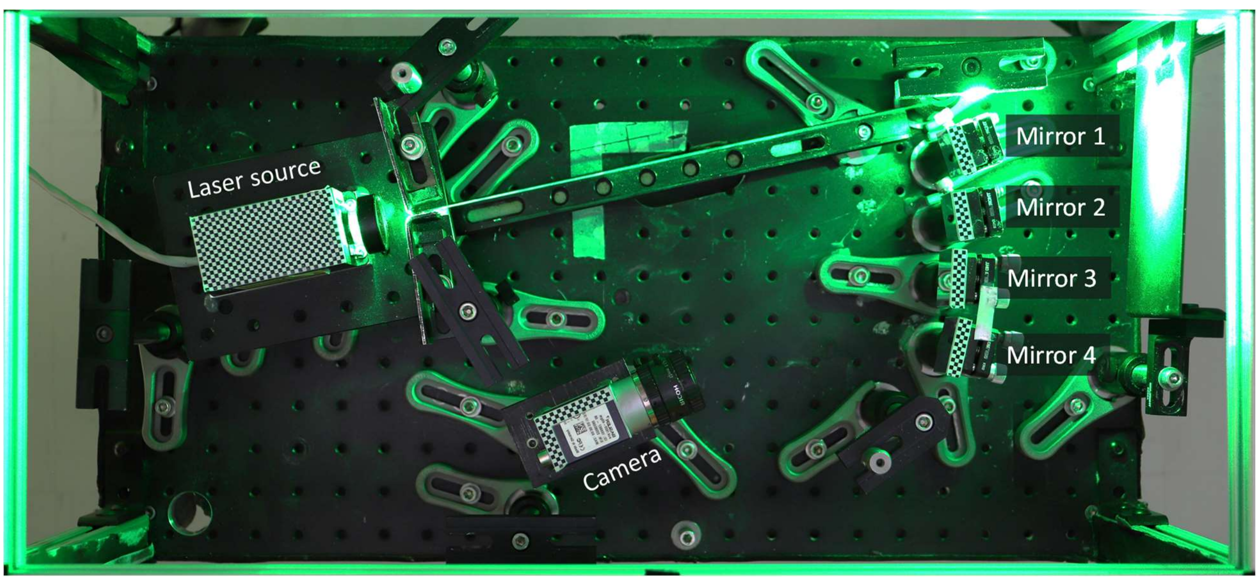

Figure 3. Top view of iSIPS breadboard, including the laser source in operation, the four mirrors (right side) and camera (bottom center). The checkerboard grids are used to verify the setup geometry and adjust, when needed, the instrument geometric calibration.

The iSIPS technique provides size distribution in terms of number of detected particles per size interval. The mass distribution could be available via assumption on particulate material and its density.

D. Selection of particulate materials

The experiments were carried out with three commercially available types of particulate materials:

- Arizona Road Dust (ARD) - provided by Powder Technology Inc., Arden Hills, MN, USA

- OPRH3N general representative lunar highland regolith simulant (LRS) - provided by Off Planet Research, LLC, Everett, WA, USA
- Combustion Residue Simulant (CRS): simulant of pre-combustion and combustion soot, the Raven 410 Carbon Black - provided by Powder Technology Inc., Arden Hills, MN, USA.

The particulate samples were visually analyzed using microscopic observations (Figure 4).

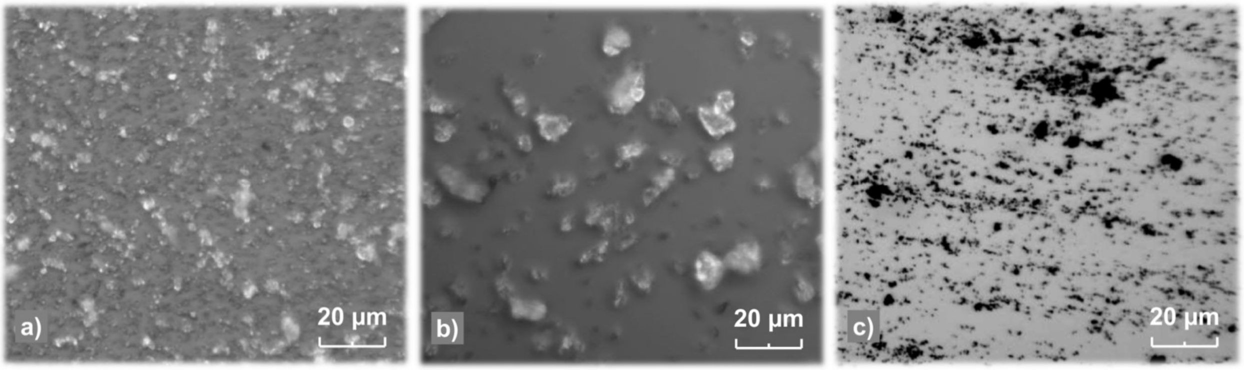

Figure 4. Microscopic pictures of aerosol samples: mineral Arizona Road Dust (a), coarse lunar regolith simulant (b) and Raven 410 carbon fine soot (c).

E. Test sequence

Experiment high-level planning and design were done according to selected requirements found in the open literature.[3,5] Table 1 below summarizes the objectives and main experimental tasks currently being done. A dry run was first performed to verify the functioning and limitations of the existing setup. Then, a first test was performed on pure material particulate, varying both the size and the concentration of the sample. Finally, a second test aimed to analyze the behavior of particulate mixtures of available materials. Discerning the microphysical properties of a mixture of different samples and capturing the changes in material composition of a sample during an acquisition (by

Table 1. Objectives and planned experimental tasks

	Dry run	**Test # 1** **1-composition dust**	**Test # 2** **Dust mixture**
Objectives	▪ Validate the feasibility of the tests for a set of concentration and size ranges (ARD) ▪ Validate acquisition parameters (camera acquisition time) ▪ Estimate the number of tests to be done in line with project scope ▪ Validate proper operation of all lab equipment ▪ Validate proper operation of the processing chain ▪ Acquisition of ambient aerosol	▪ Obtain data for a set of concentrations and size ranges for pure materials: ▪ Test 1a) ARD ▪ Test 1b) LRS ▪ Test 1c) CRS	▪ Obtain data for a set of concentrations and size ranges for mixture of three (3) types of aerosols: ▪ Test 2a) ARD-LRS ▪ Test 2b) ARD-CRS ▪ Test 2c) LRS-CRS ▪ Test 2d) ARD-LRS-CRS
Experimental tasks	▪ Data acquisition of background aerosols ▪ Data acquisition without AAC filtering o Check response with dust concentration o Check Palas operation with reference dust o Check GRIMM operation o Check iSIPS operation and agreement with GRIMM o Acquisition for several concentrations (controlled by the Palas speed o Data acquisition with AAC filtering o Check response with dust size o Check Palas operation with reference dust (ARD) o Check AAC operation (filtered dust size) o Check GRIMM operation o Check iSIPS operation o Acquisition for several sizes (0.1 to 2.5 µm; 2.5 to 10 µm) ▪ Microscope observations		

injecting into the setup different materials within the same sequence) will be addressed in a next development stage by adding new modalities (polarization, fluorescence) to the setup.

III. Experimental Results

A. Single-composition tests

Preliminary results for the single-composition tests showed some interesting findings, confirming the sizing capabilities of the iSIPS instrument already highlighted by Cantin et al.[11] The preliminary experimental dataset consists in size distribution retrievals for different particle sizes at the same concentration. The particle size retrieval, combined with the scattering intensity observed in each angular interval, allows us to assess a certain tendency between the intensity ratios and particle size.

Each counted particle contains the scattering intensity values (or power) as recorded by the camera in the four ROIs. The ROIs are labelled from 1 (closest to the laser beam) to 4 (maximum scattering angle). Intensity ratios

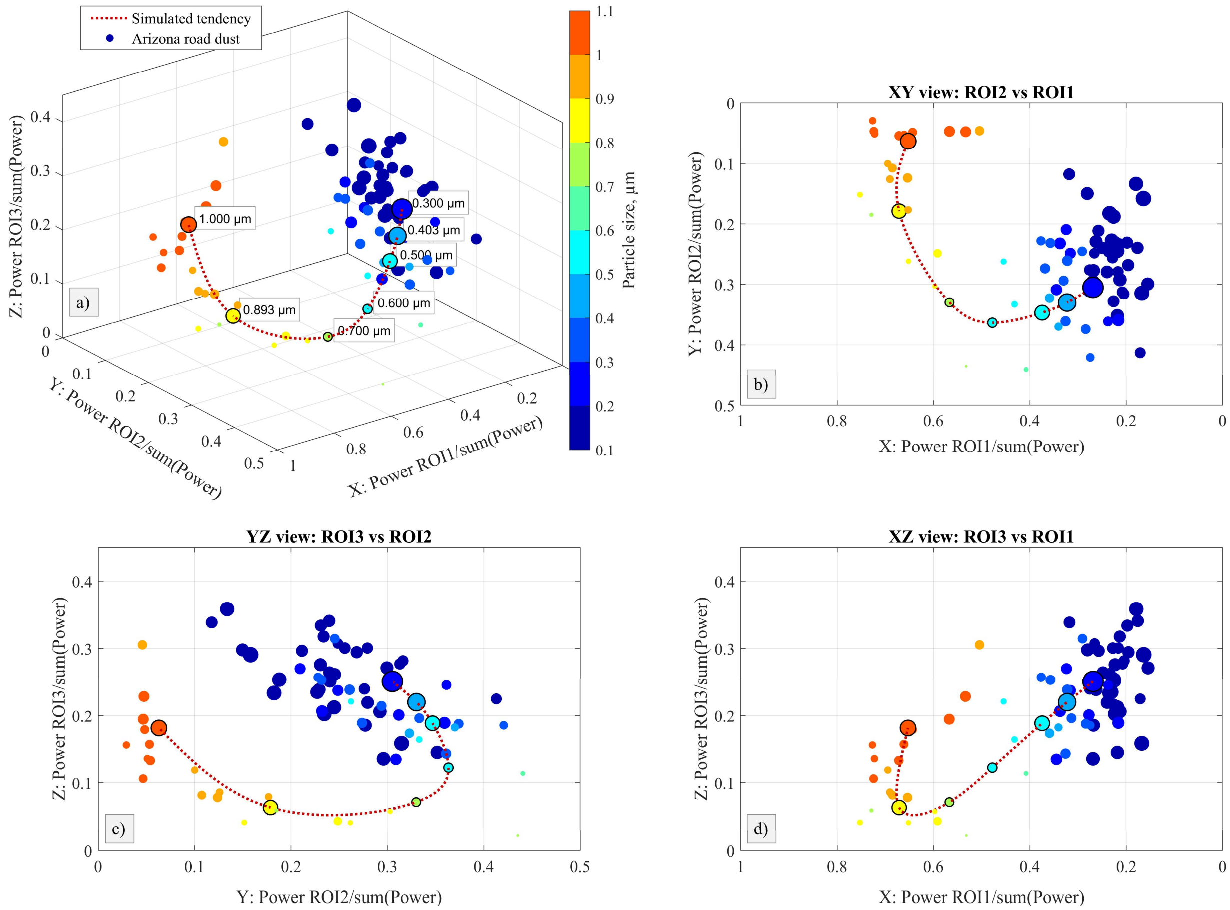

Figure 5. Representation of the measured intensity ratios from the sub-images of the ROIs, or mirrors, obtained for different retrieved particle sizes of Arizona Road Dust particles. Size of dots is representative of the Power ROI4/sum(Power). Labelled black-edged circles and dotted red line represent the simulation results presented by Cantin et al.[11] (obtained from simulations with a mineral dust-like aerosol). The 3D view (a) is completed with 2D views of XY plane (b), YZ plane (c) and respectively XZ plane (d).

comparisons for sizes up to 1 µm are presented in Figure 5 for ARD particles, in Figure 6 for lunar regolith simulant and respectively in Figure 7 for soot CRS particles.

The experimental results are compared with a simulated signature provided by simulations of dust-like particles at unique position and taking into account several setup parameters (laser source bandwidth, setup geometry, camera entrance pupil).[11] As expected, the mineral behaviors of the ARD and LRS are in good agreement with the simulated results, and the retrieval dots distribution can be explained by the differences in particle positioning and processing assumptions. As showed by microscopic observations (Figure 4), the soot size distribution is narrower than that of the

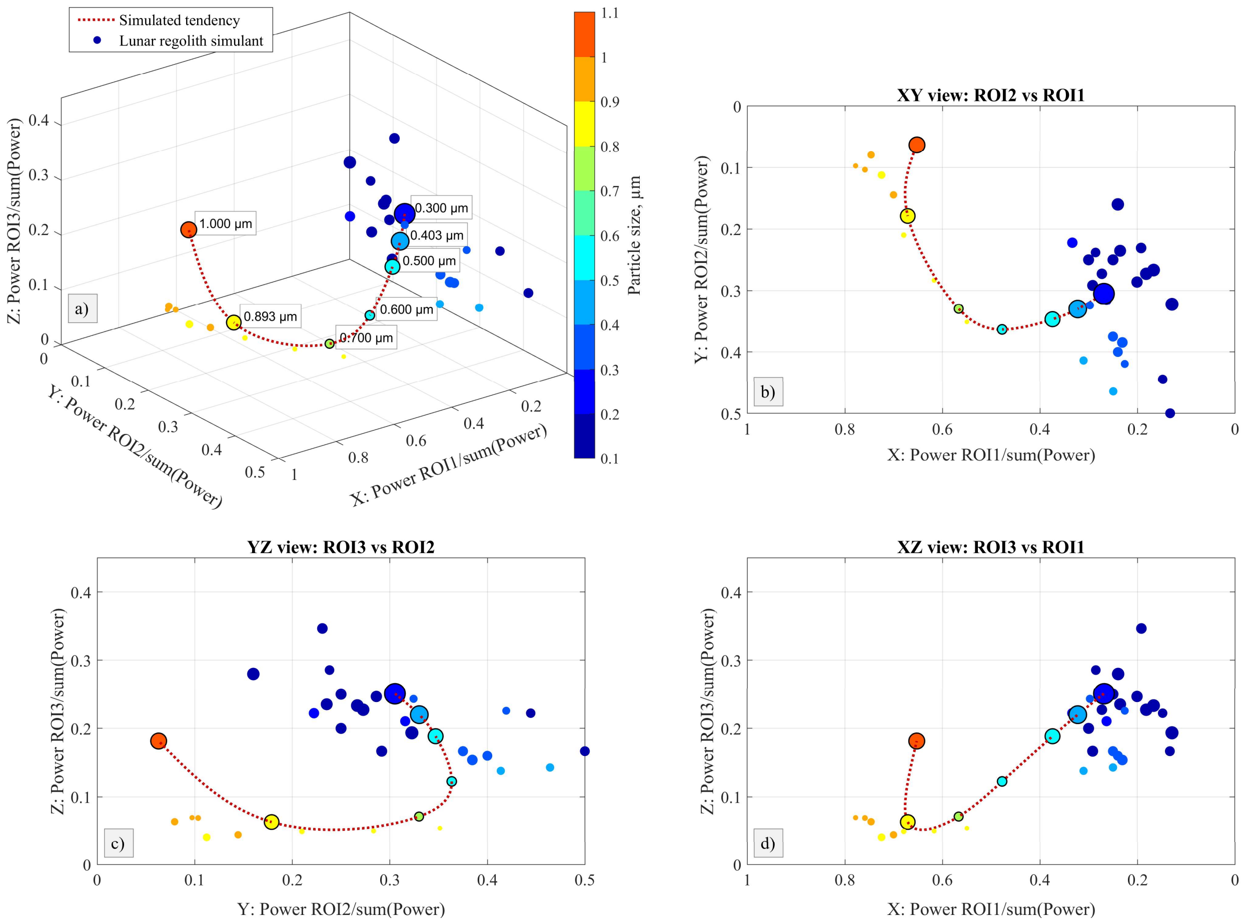

Figure 6. Representation of the measured intensity ratios from the sub-images of the ROIs, or mirrors, obtained for different retrieved sizes of lunar regolith simulant particles. Size of dots is representative of the Power ROI4/sum(Power). Labelled black-edged circles and dotted red line represent the results presented by Cantin et al.[11] (obtained from simulations with a mineral dust-like aerosol). The 3D view (a) is completed with 2D views of XY plane (b), YZ plane (c) and respectively XZ plane (d).

mineral one. This appears also in Figure 7, where the blue dots (representing fine particles) seem to be predominant. However, the most encouraging result is that the experimental soot signature as shown in Figure 7 is drastically different from that of the simulated tendency, proving that iSIPS is able to differentiate the changes in aerosol composition.

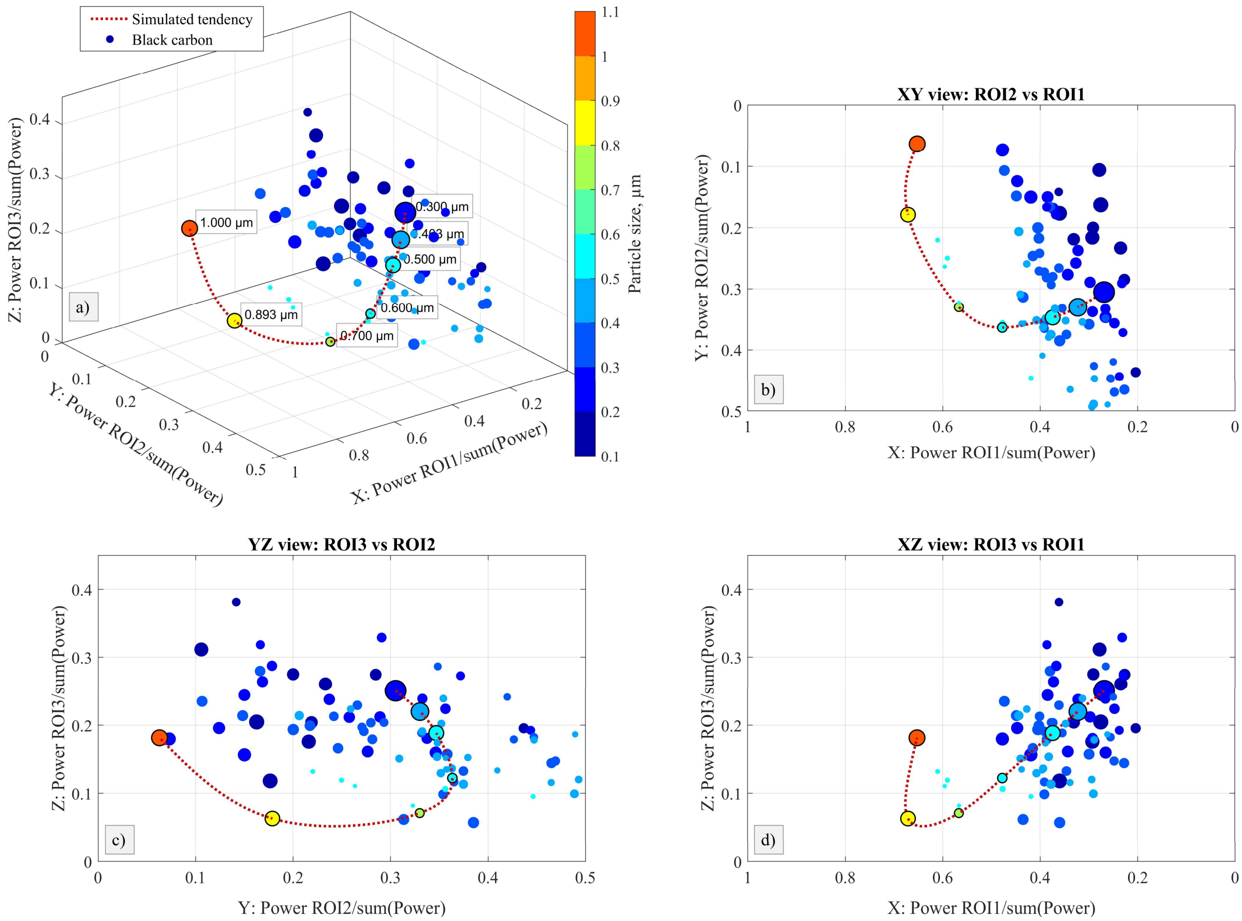

Figure 7. Representation of the measured intensity ratios from the sub-images of the ROIs, or mirrors, obtained for different retrieved sizes of CRS soot particles. Size of dots is representative of the Power ROI4/sum(Power). Labelled black-edged circles and dotted red line represent the results presented by Cantin et al.[11] (obtained from simulations with a mineral dust-like aerosol). The 3D view (a) is completed with 2D views of XY plane (b), YZ plane (c) and XZ plane (d) respectively.

B. Dust mixture tests

The mixture tests aim to explore the capacity to detect the changes in particulate nature using iSIPS measurements and monitoring. We present here the results obtained during a mixture test designed to simulate the onset of a smoke incident during normal operations. The aerosol mixture consists of stacking a LRS layer over a CRS layer into the Palas material reservoir. The particles are then generated into the iSIPS enclosure, and the data is continuously recorded by both GRIMM and iSIPS instruments. At the beginning, it is expected to encounter only LRS particles in the enclosure, characteristic of a normal operation. The approximate transition between the LRS and CRS layers is marked with a label on the Palas feed piston. This transition takes a certain time where both LRS and CRS particles might be present in the enclosure, characteristic of a smoke incident starting over a dusty background. Towards the end of the experiment, it is expected to have only soot particles dispersed into the enclosure.

The test results are presented in Figure 8, where the regolith dispersion is highlighted in green, followed by the estimated transition in blue and the soot dispersion in black. The upper panel (Figure 8a) shows the GRIMM time series of PM1, PM2.5, and PM10 measurements respectively. The regolith particles are expected to have a wide size range, leading to notable differences between the mass concentration of fine (PM1) and large particles (PM10). This is visible in the regolith green zone but continues as well after the transition. An increase in PM1 values is observed after the transition. One minute after the transition, it is observed that the difference between PM10 and PM1 measurements decreases, in agreement with an aerosol population with submicron size as the soot samples. The increase of PM1 is recorded as well by iSIPS measurements. The actual setup encounters some limitations in providing accurate size retrievals beyond 1.1 µm. Further technological developments will allow, in the near future, and with much more confidence, to use the iSIPS observed difference between PM1 and PM10 to have clues on the changes in the aerosol nature. However, even with the present limitations, it is possible to monitor the increase of fine particles and to adapt the processing using a threshold triggering method. Thus, the aerosol signatures before the transition (Figure 8c and Figure 8d) present similarities with mineral aerosols as presented in Figure 6. This is the case as well as during the transition (Figure 8e), where larger particles, close 1 µm, are detected. The signature changes notably afterwards (Figure 8f and Figure 8g), with a scatter cloud dominated by fine particles (around 0.3 µm). These preliminary results prove the iSIPS capacity to detect a change in the nature of aerosol population.

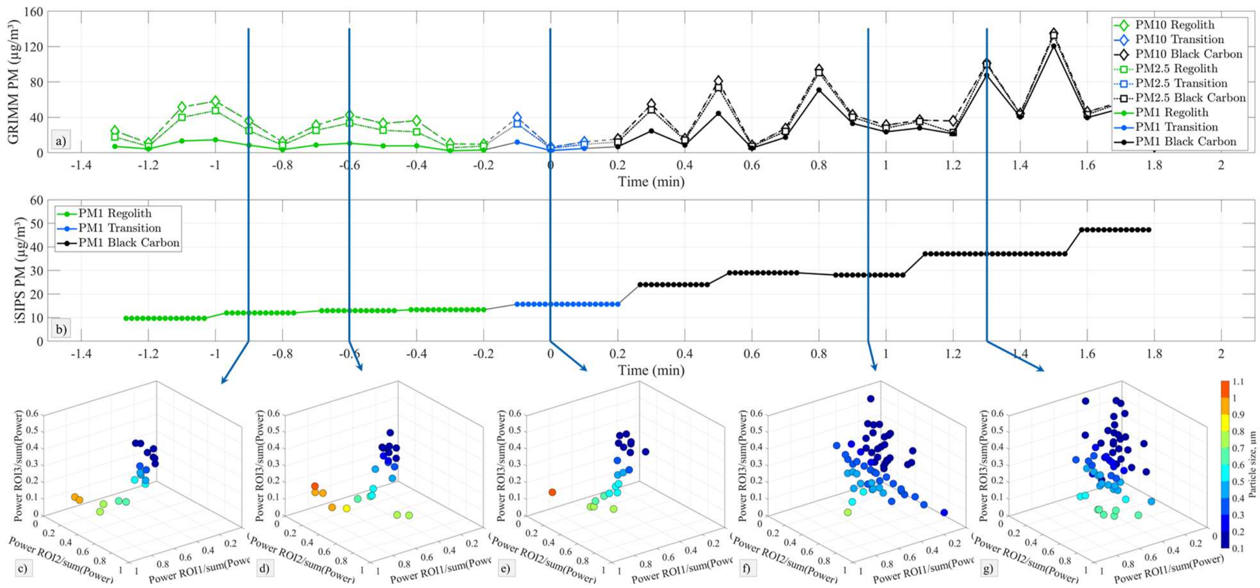

Figure 8. Results obtained with a mixture of stacked LRS and CRS layers. Time series of particle concentration are recorded by both GRIMM (a) and iSIPS (b) instruments; the time reference (i.e. zero value) represents the transition between the layers. The evolution of the aerosol signature is presented as 3D scatterplots of intensity ratios at different moments in test duration (c, d, e, f, g). The evolution of the aerosol signature is presented as 3D scatterplots of intensity ratios at different moments of the test (c, d, e, f, g).

IV. Conclusions and Future Work

In this manuscript, the experimental planning was described, and some preliminary results were presented to demonstrate that PM size distribution as well as clues about their composition are possible with iSIPS measurements.

Because it does not need a pump or a ventilator to sample air, iSIPS has no moving mechanisms, is less prone to mechanical failures, and can operate either under atmospheric (cabin, habitat) of deep vacuum (airlock) conditions, making it very attractive for space applications. Moreover, there is no need to perform regular maintenance to ensure proper calibration of the pumped flow to assess the number of particulates per unit of volume. This also prevents fouling of filters or dust accumulation on hard to access optical surfaces for cleaning. This avoids opening the instrument for maintenance and cleaning. Another merit of iSIPS is that particulate matter larger than 20 µm could be measured without being lost in the inlet of the instrument due to their large inertia. As a matter of fact, the packaging of the system can be achieved so that optical windows prevent dust to reaching critical components such as the mirrors and camera. Since the instrument has no moving mechanisms, it is expected to have a better reliability and life expectancy than those given by low-cost sensors for space applications where the instrument will be exposed to the abrasive regolith. Furthermore, iSIPS offers several functionalities and a better precision than that of low-cost sensors. In a previous, study,[13] iSIPS, along several low-cost sensors (Dylos DC1100 Pro, Honeywell 32322550, UNI-T UT338C, FOOBOT FBT0002100, Origins Tech LE100 (Laser Egg)), were tested and compared to a reference instrument (GRIMM Series 1.100). The study revealed that the Dylos sensor gave a good precision but was significantly affected by composition of the particles and could not offer size distribution retrieval. Moreover, it ceased to function after a couple of weeks of intermittent operation. It is worth to mention that the Honeywell sensor showed the best linearity and correlation robustness but, as the other low-cost sensors, could not perform size distribution measurements. For concentrations lower than 125 µg/m3, and whatever the composition of the particulates, iSIPS appears, so far, to be the instrument giving the most precise measurement (≤25%) while offering size distribution options. All of these makes iSIPS very well suited for PM monitoring in space applications, whether in pressurized cabins of spacecraft or rovers, in the varying atmospheric pressure of airlocks or in the deep vacuum of space, outside habitat or rovers. Its modular design could easily be adapted for different volume ranges, depending on the desired application. Moreover, targeted particle sizes can be addressed by adapting the mirror configurations toward a better combination of scattering angles. With the current laser wavelength, angles up to 15° are expected to have a major impact on size range with less influence on the aerosol nature. In the current setup, this is covered by only one mirror, close to the forward direction and thus recording scattered intensities of higher values compared to the other mirrors. The size retrieval will then depend on a series of factors, such as the camera parameters (exposure, bit depth) and the viewing geometry. For instance, smaller particles will provide less intensity than the larger ones, and their detection will involve increasing the laser power. However, this might result in image processing issues when larger particles are present within the interrogated volume. Their scattered contribution might saturate the image or completely cover the contributions of smaller particles in the same ROI. The present setup was built over trade-offs between the size limitations, laser power and image detection and covers, as it is, a limited range for the particle sizes.

The mirror positions were chosen to provide a wide range of (delimited) scattering angles with enough capacities to image distinct scattering contributions from individual particles. The mirrors are spaced to easily detect the image ROIs related to each mirror. The mirror size is a major limitation for the small scattering angles, when the need to cover angles close to the forward direction struggles with the parasite reflections from the incident beam and with the risk of overlapping several scattered “spots” in the image. New designs and new modalities are in study to push the size boundary up to 10 µm. This might involve adding mirrors or a secondary camera or modulating the laser power to address specific particle sizes.

The technological development road map also includes some basic functionalities. The alarm definitions are to be defined according to exposure limits, as a stand-alone instrument or as a part in a global environmental monitoring system. The exposure events will be monitored with respect to their temporal evolution, with an emphasis on the inhalable fraction. A predictive routine will be designed to help the exposure forecast, but also to confirm and cross-reference the events with additional external data provided by the environmental system.

Several experimental steps have been planned, and experiments are underway to further characterize and differentiate mixtures of PM consisting of Arizona road dust, simulant of lunar regolith, and simulant of residues of combustion. Parallel efforts will be devoted to refining the algorithm to improve the processing time to ensure that it is compatible with monitoring applications (safety and health) in spacecraft and habitats. If the requirements do ask for a particle mass concentration instead of a particle count of a given size concentration, methods will be devised to convert the number distribution in mass concentration. The approach likely used would mimic that recently utilized by NASA (assumes the density of Arizona Road Dust as a starting point, for calculation) for its PM studies in the International Space Station (ISS).[7,8] To improve the compositional discrimination capability of our system, polarization and fluorescence modules as well as new procedures could be implemented. Efforts are also warranted in areas of performance verification and calibration before the whole setup can be miniaturized and integrated into a prototype aimed at environmental testing that includes reduced gravity parabolic campaigns.

Appendix: intensity ratios for mirror combinations

As predicted by Mie theory, the scattering intensity presents large variations with respect to the scattering angle and the particle size. The iSIPS approach uses intensity ratios rather than absolute intensities to retrieve the particle size. In order to illustrate the relative intensity trends for the actual setup, the intensity ratios were obtained during the tests with regolith simulant particles. The results are presented in the table below, where the mean reflects the weight of considered mirrors in the approach. The wide range of angular conditions is illustrated by the standard deviation values.

Table 2. Statistics on intensity ratios for each combination of mirrors

	Mirror 1/ Mirror 2	**Mirror 1/ Mirror 3**	**Mirror 1/ Mirror 4**	**Mirror 2/ Mirror 3**	**Mirror 2/ Mirror 4**	**Mirror 3/ Mirror 4**
Mean	11.9	36.3	45.7	5.9	10.7	2.6
Standard deviation	27.0	76.6	87.8	10.6	22.8	6.9

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