**Development and Testing of the MicroMED sensor: from BreadBoard model to Flight Model**

**Authors**

**Fabio Cozzolino1, Gabriele Franzese1, Fausto Cortecchia2, Cesare Molfese1, Francesca Esposito 1, Giuseppe Mongelluzzo1, Alan Cosimo Ruggeri3, Carmen Porto1, Simone Silvestro1,4, Ciprian Ionut Popa1, Diego Scaccabarozzi5, Bortolino Saggin5, Ignacio Arruego6, José Ramon De Mingo6, Alberto Martín-Ortega Rico6, Nuria Andrés-Santiuste6, Joaquìn Rivas6, Daniele Brienza7.**

**Affiliations**

1 INAF – Astronomical Observatory of Capodimonte (OAC), Salita Moiariello 16, 80131, Naples, Italy

2 INAF – Astrophysics and Space Science Observatory (OAS), Via Piero Gobetti, 101, 40129 Bologna, Italy

3 INAF- Astrophysics Observatory of Catania ([OACatania](https://www.google.it/search?sca_esv=af8edf7ada5c4353&q=INAF+OACatania&nfpr=1&sa=X&ved=2ahUKEwj3gdvzot2EAxUTcfEDHa1SA2YQvgUoAXoECAYQAw)), Via S.Sofia, 78, 95123, Catania, Italy

4 SETI Institute, Carl Sagan Center, Mountain View, CA, USA

5 Department of Mechanical Engineering, Politecnico di Milano, Lecco, Italy

6 Instituto Nacional de Técnica Aeroespacial (INTA), Torrejon de Ardoz, Madrid, Spain

7 Asi (Italian Space Agency ) – Via del Politecnico 00133, Rome, Italy

**\*** Correspondence: [fabio.cozzolino@inaf.it](mailto:fabio.cozzolino@inaf.it) ; Tel.: +39 0815575538

# Abstract

Suspended dust plays a critical role in regulating the Martian climate by influencing the atmospheric thermal gradient, altering the amount of infrared and visible energy absorbed and scattered by the atmosphere, and acting as condensation nuclei for CO2 ice-clouds particles. There are many well demonstrated, dust-related effects on martian climate which depend on dustsize, concentration, chemical and bulk composition. Currently, an accurate estimation of these parameters is lacking as they are derived from indirect measurement of the optical depth acquired from the surface and orbital data. These indirect measurements require a priori assumptions on the grain distribution curve and are hence subject to possible biases. To overcome these limitations, an optical particles counter called MicroMED has been developed under the National Institute of Astrophysics (INAF) leadership. MicroMED can measure the sizes of individual dust grains in a specific volume of air thus providing the grain size distribution and concentration. MicroMED has been selected to join the Dust Complex payload on board the ExoMars 2022. The Flight Model of the instrument has been developed and optimized starting from two prototype BreadBoard versions. Here we present the sub-systems that constitute MicroMED and their testing and characterization process, performed using the Breadboard models. We discuss the optimizations and improvements introduced on the basis of the prototype results and the overall performances of the final design.

# Keywords

# Mars, Particles Counter, MicroMED, ExoMars, Fiber, Test.

# Introduction

The ExoMars mission, now being rescheduled and reconfigured after the international crisis in Ukraine, aims to search for signs of past and present life on Mars and consists of a rover named Rosalind Franklin and a surface platform (SP), Kazachok (Vago et al., 2017; 2015) The goal of the SP is the characterization of the Martian surface environment through the study of the Martian atmosphere (Runyon et al., 2021). To achieve this goal the Kazachok lander will be equipped with the Dust Complex (figure 1), a suite of four sets of sensors, devoted to the study of the aeolian environment at the surface of Marsmonitoring the diurnal, seasonal, and annual dust cycles (Zakharov, A.V. et al., 2022).These sets of sensors are the: 1) Impact Sensor (IS-1), which includes piezoelectric sensors (PS), charge-sensitive transit sensors (QS) and an optical dust sensor (OS), for the measurement of the sand-grain dynamics and electrostatics charger dust mechanisms, 2) MicroMED (Micro Measurement Environment Dust), for the measurement of airborne dust size distribution and concentration, 3) ECS (Electrical Conductivity Sensor) designed to measure the electrical conductivity of the Martian atmosphere, and 4) an expandable extension boom equipped with the second impact sensor (IS-2), two electrical probes (EF-1 and EF-2) and an antenna (EMA) to study of electromagnetic noise associated with the dynamics of dust particles in the near-surface atmosphere. Uunfortunately, due to the currently unstable geopolitical landscape, the ExoMars mission has undergone a drastic change, which could result in the exclusion of some instruments. The mission, if completed, would offer a unique opportunity to study dust-related phenomena by monitoring dust dynamics for one Martian year (duration of the nominal mission) and by providing the first ever direct measurement of near-surface dust distribution on Mars.

Dust on Mars plays a key role in modulating the climate and its concentration varies on a daily and seasonal basis (Smith, M. D., et al., 2023 ;Claire E. Newman.et al., 2022; L.Komguem et al., 2013). The presence of suspended dust grains due to large (dust storms) and more localized (dust devils) dust-rising events (Franzese, G. et al. 2021) profoundly affects the Martian climate by absorbing and scattering solar and thermal radiation and by acting as condensation nuclei for H2O and CO2 (L.Komguem et al., 2013). This in turn influences the thermal structure, the balance and the circulation of the atmosphere (Rodinov et al., 2017; Kjartan M.Kinch et al., 2015; Geisler, 2014; Jakosky and Haberle, 1992; Jakosky and Martin, 1987). The knowledge of the GSD (Grain Size Distribution) and dust grain concentration, together with the imaginary part of the refractive index, is thus fundamental to better constrain the atmospheric energy balance and the local wind pattern. Deposited dust has also long-term effects on the climate, by changing the albedo at the surface and triggering climatic warming in a positive feedback (Franzese, G. et al., 2018).

Currently, information on the dynamics of dust grains at the surface, concentration and GSD are not very well constrained and have been obtained indirectly from measurements of the optical depth of the Martian atmosphere. The calculation of optical depth has been performed so by a broad set of spacecraft missions and instruments from both the surface and orbit (see Farrel, W., 2017) for a review): Mariner 9 (Pollack, J., 1995 ; Toon, O., 1977) Viking orbiters (Clancy, R. T., & Lee, S. W., 1991; Pang, K.et al.,1976), Viking landers (Pollack, J., 1995), Pathfinder (R. Todd Clancy, 2003), the Mars Exploration Rovers (Lemmon, M. T., 2015), Mars Global Surveyor Thermal Emission Spectrometer (Clancy, R. T., 2010, 2003; Whiteway, J. et al. 2008, 2003), Mars Express (Määttänen, A.et al., 2013; Rannou, P. et al.,2006), the Mars Reconnaissance Orbiter (Guzewich, S. D.,et al., 2014; Wolff, M. J. et al., 2006), and the Mars Science Laboratory Curiosity rover (Chen‐Chen, H., et al., 2019 ; McConnochie, T. H. et al., 2018; Vasilyev, A. 2009).

The reff (effective radius of dust distribution inferred from optical depth measurements) takes values between 0.6-8 μm (Lemmon, M. T., et al., 2019). For instance, TES retrieved reff values between 1.3-1.8 μm (Wolff, M. J., & Clancy, R. T. 2003), while the LIDAR instrument on the Phoenix mission retrievedvalues between in a range of 1.2–1.4 μm (L.Komguem et al. 2013). MastCam and REMS UVS onboard Curiosity indicate that the dust effective radius varies significantly with season, ranging from ~0.6 μm during the low opacity season (*Ls* = 60°–140°) to ~2 μm during the high opacity season (*Ls* = 180°–360°) (Vicente‐Retortillo, et al., 2017).

With a few exceptions, most of these results have found that dust particle size varies by approximately 50% around a canonical value of ~1.5 μm in effective radius. Occasional evidence of smaller particles (e.g. Rannou, P.,et al., 2006 ) and larger particles, particularly in global dust events (Clancy, R. T., et al., 2010), has also been observed. The value of reff, changes after global and regional dust events. From imaging and spectral observations by the Curiosity rover through the 2018 global dust storm the dust effective radius was observed to increase rapidly above 4 μm remaining above 3 μm over a period of ~50 Martian solar days, then returning to nominal values of reff, (Lemmon, M. T. et al., 2015). Regarding dust particles concentration at middle latitudes under nominal, non-dusty conditions, a concentration of 1–2 cm–3 (Moroz, V.I. et al., 1993) has been estimated, which in mass terms is ~1.8 × 10–7 g m–3. This value increases significantly during dust storms, reaching ~7 × 10–2 g m–3.

We have seen that the effective radius retrieved from optical depth measurements exhibits strong variability. Using MicroMED we will directly measure the dust size distribution, providing ground-truth to these retrievals.

# MicroMED: BreadBoard Version (BB) .

# *2.1 Instrument Description*

MicroMED, is an optical particle counter that uses the principle of light diffusion to detect dust grain. It can aspire dust grains through a sampling system, redirecting them into a region (here called sampling volume) which is illuminated by an optical system. The light scattered by grains crossing the sampling volume is collected by a mirror and focused on a photodiode, whose response depends on the grain size and chemical composition. MicroMED (figure 2) was designed to be small (80 x 60 x 100 mm3) and light (500 gr), with a low power consumption (∼3.5 W). It consists of three subsystems: the sampling system, the optical system and the processing, acquisition and storage system. These subsystems have been developed and tested based on the following technical requirements:

1. To suck dust grains in size range of 0.4 to 20 µm;
2. To carry dust grains towards the instrument sampling volume;
3. Fluid flow inside the instrument ducts must be laminar, to avoid eddies which would cause deposition of grains on the walls, inefficient concentration of grains inside the sampling volume, and potentially multiple acquisitions of grains saturating the output signal;
4. The optical power density inside the sampling volume must be not lower than 0.4 W/mm2 to detect the 0.4 µm grains;
5. To maximize particle detection, the sampling volume dimension perpendicular (d⟂) to the particle motion should be comparable with the size of flow aspired. The dimension parallel (d//) to the particle trajectory should be sufficiently wide for the transit of the grain to produce a signal with a time duration to be processed by the system acquisition;
6. The system acquisition must be able to amplify the current signal (~ nA) produced by the photodiode and acquire it with a sampling frequency ≥ 2 MHz without distorting the waveform.

The three subsystems have been firstly designed, developed and tested separately in order to evaluate their characteristics and then integrated into BB model (figure 3b). Next, tests were performed under Martian environmental conditions (excluding temperature) to verify the performance of the breadboard model.

# 2.1 Subsystems of MicroMED BB

## 2.2 Sampling System

The sampling system consists of an inlet duct, an outlet duct and a pump. To verify the sampling system, a fluid dynamic model (figure 3a) was developed and described in Cozzolino et al., 2021. The testing activity focused on verifying the absence of eddies inside the main box of the instrument and on measuring the particle flow diameter coming out from the inlet. The eddies formation could disperse the dust grains, pushing them away from the sampling volume, also causing a possible dust deposition on sensitive elements such as the mirror or the photodiode. Moreover, eddies could cause multiple crossings of the spot by the same grain, altering the measurement. Determining the diameter of the particle stream allows us to define the minimum value that the d⟂ must have to detect most of the particles contained in the stream.

The physical characteristics of inlet and outlet ducts are summarized in table 1. The inlet and outlet ducts consist of two parts, internal and external, compared to the MicroMED’s main box. Data in the table show that the ducts differ in size and shape (figure 4). The inlet duct is capped by a sampling head equipped with 4 holes on its side. This allows an efficient suction of the grains while protecting the ducts from dust deposition during the phases when the instrument is inactive. The MicroMED prototype shown in figure 3bhas been used to verify the sampling system.

# 2.3 . Optical System

The aspirated dust is redirected towards the sampling volume generated by the optical system which has been developed to comply with points IV and V listed in subsection 2.1 and achieve a light intensity distribution inside the sampling volume as uniform as possible. The optical system generating such a sensing beam is made up as follows:

* A laser source (Roithner RLT830-150GS) with a typical optical power of 150 mW, wavelength of 830 nm and typical parallel and perpendicular beam divergences of 25° and 40°, respectively.
* A first lens system consisting of two aspherical lenses, called 300 group (figure 5a),

that can collect the laser beam and focus it into the fiber.

* A second lens system, called 210 group (figure 5b), made up of a bi-spherical lens and a bi-cylindrical lens, able to shape the sensing beam inside the sampling volume between the inlet and outlet ducts. The unit provides spacers accommodation to centering the sampling volume between inlet and outlet.
* A Thorlabs multimode optical fiber with a core of 50 µm, a Numerical Aperture (NA) of 0.22 and a length of 2 meters to link the two optical groups.
* A golden mirror with a 135 ° field of view.
* A Hamamatsu Si PIN photodiode SN5106.

In the BB version, the 300 group is placed in front of the laser (figure 6) employing a XYZ linear stage. The 210 group, linked to the 300 group by the fiber, is connected to the box, as shown in figure 7, inserting shimming spacers to fine-tune the position of the sensing beam between the inlet and outlet ducts. The mirror and the photodetector are positioned on the same axis, perpendicular to particles flow and sampling volume. The internal parts of the box have been painted with Aeroglaze 306 to reduce the stray light.

# 2.4 *Processing,* *Acquisition and Storage System.*

The current signal, from the photodiode, is processed by the Proximity Electronics (PE) (Molfese et al., 2012), housed outside the box (figure 7). The board was designed:

* To convert current signal in voltage signal
* To amplify the signal and compensate the offset generated by noise current.

The PE has a first transimpedance pre-amplification stage with a gain factor of 103 able to convert the current signal from the photodiode into a voltage signal with a full scale between 0 to 10 V.

Sequentially at the pre-amplification stage, two linear amplifier stages are present in cascade with amplification gain of 102 V/A and 104 V/A, respectively. These add to the first pre-amplify stage set two voltage outputs called Low and High Gain Output. Low gain output has a gain of 105 V / A, while High Gain output has an amplifier factor of 107 V/A. The PE is powered with two voltages of +12V and -12V.To guarantee a correct sampling, the amplifiers have been chosen with an adequate passband (3 MHz), relative to the duration time of signal generated by particles crossing the sample volume. The board is equipped with an input for offset compensation, useful to generate a compensation current in the input node of the amplifier to reset the noise current. The noise current has two components, one electrical and one optical, depending on the stray light.

The PE is connected in cascade to another board, PCI 6132 DAQ (NI), which is dedicated to signal acquisition and storage.

# Tests and Results

## 3.1 Sampling System.

The sampling system has been validated through a dedicated prototype of MicroMED tested in the INAF-OACN vacuum chamber (Cozzolino, F. et al., 2020). This prototype is able to reproduce the Martian atmospheric conditions in terms of pressure, chemical composition and dust presence. The experimental results (Cozzolino, F. et al., 2021) are in good agreement with technical and scientific requirements. Results show how the sampling system can aspire particles in a range of diameters 0.4-20 µm, redirecting them into a sampling volume with a diameter slightly larger than 1 mm.

# 3.2 Optical System

In order to characterize the sampling volume generated by the optical system, we performed the following tasks:

* Alignment between the Laser and the 300 group;
* Characterization of the fiber output beam in terms of the optical power and NA (Numerical Aperture);
* Alignment between the Fiber and the 210 group;
* Measurement of the sampling volume Size (d⟂; d//), intensity profile and optical power;
* Measurement of the Focus Distance.

The laser beam is coupled to the fiber through the 300 group. The laser is fastened to an XYZ translation stage, whereas the 300 group connected to the fiber is kept fixed. The alignment is achieved by moving the laser in steps of 2 µm along the three axes until the optical power at the exit of the fiber is maximized. The fiber output beam profile, detected using a Laser-Cam (HR II Coherent). The fiber output power, detected by means of a Power Meter (UP12E-10S-H5 Gentec) is 145 mW. Subsequently, we proceeded to measure NA. The value declared by the manufacturer is 0.22. To verify the NA, we fixed the fiber at a distance D = 5 mm to the Laser Cam sensor, and we measured the diameter *d* of the image. From equation 1 the laser light emission angle α was derived.

Figure 8 shows the output image and beam profile along X, Y axis at the exit of the fiber. The blue-colored circumference indicates the value of the measured beam diameter, that is equal to 2.127 mm. Considering equations 1 and 2, it is possible to obtain the experimental value of NA, which in this case is 0.21. The NA parameter becomes influential on the sampling volume profile when it reaches the value of 0.18-0.17.

Eq. (1)

**Eq. (2)**

NA=

The FC/PC connector of the fiber exit face is connected and aligned to the 210 group lens system. The alignment is performed using four screws that allow to move the fiber along the X and Y axes, considering the propagation of the light beam as the Z axis, as shown in figure 9. The alignment is completed when output beam's path of the fiber coincides with the lens system's optical axis.

The sampling volume transverse profile generated by the optical system after the alignment is shown in figure 10. The resulting spot has an elliptical shape with the major axis d⟂ of 1.036 mm and the minor axis d// of 0.351 mm. The major axis d⟂ perpendicular to the particle flow, is > 1mm, i.e. larger than the cross-section of the particle flow inside the sampling volume, according to the scientific requirements.

The 210 group optical power output, measured using the power meter, is 138 mW, corresponding to an average optical power density greater than 0.4 W/mm2,considering the sampling volume size (1.036 x 0.361 mm2).

The laser cam and a micrometer stage have been used to measure the focus distance. We moved the group 210 with respect to the laser cam until the image is in a focus point, with the displacement representing the focus distance. The obtained value is 29 mm.

# 3.3 Processing Acquisition and Storage System

To verify the performances of the processing, acquisition and storage system, the electrical board, closed in Faraday cage, has been tested. A square wave with an amplitude of 0.05 mV, obtained using a function generator, has been given as an input.

Using an oscilloscope, it was possible to verify the proper operation of the amplification stages of the two channels Low and High. In addition, fixing the value of the amplitude (0.05 mV) and by varying the frequency of the input signal between 100 KHz and 2 MHz it has been verified that the processing and acquisition system not acting on the output signal deforming the shape.

## MicroMED BB.

The three subsystems, after being characterized separately, were integrated in the BreadBoard (figure 11) to asses the performance of the instrument. In particular we analyzed the acquired data (to study the amplitude and duration of the signal by varying the grain size) and we compared the experimental data with theoretical data (Mie curve) obtained considering the characteristics of the optical system.

MicroMED’s BB was placed inside the Martian simulation chamber while the laser was on the XYZ translation stage outside of the chamber to align the optical input group. The laser was also isolated from the floor because the XYZ stage can be sensitive to the pump's vibration to reach the Martian condition inside the chamber. With the laser placed outside the box, a feedthrough for the fiber was built. The types grains used in our tests were monodisperse SiO2 spherical particles (Microparticles gmbh) in a range of 0.4-20 µm in diameter. The properties of calibrated particles are summarized in table 2. We chose this kind of particles because silica is the most abundant element of Martian dust grains (Berger, A. et al., 2016). The conditions inside the Martian simulation chamber during tests were: 6 mbar, 293 K, CO2 environment, and presence of monodisperse dust. The tests were repeated for particle size reported in table 3. Some examples of a signal relative to particles of 0.787 µm and 19.3 µm are shown in figure 12. The 0.787 µm and 19.3 µm signals were acquired in the High and Low channel respectively. The time duration of signals depends not only on the region of sampling volume crossed, but also on the size of the particle. This aspect hints at a correlation between signal duration and particle size which is currently under study. To estimate the generated mean signal amplitude several tests were performed for each monodispersed size reported intable 3. Furthermore, the table 3shows the average photodiode current amplitude values (in ampere) of the signals generated by the particles detected by MicroMED’s BB and of the noise value in both channels. The noise value is about one order of magnitude smaller than mean signal of particles with a good signal to noise ratio.

1. Flight model vs BreadBoard model.

Based on the results of BB model of MicroMED testing performed in 2014, the flight model (FM shown in figure 13b), it was developed and optimized in 2018 to make it lighter and able to successfully pass space qualification tests (vibration and thermal vacuum tests) performed in 2019. These tests were in accordance with the mission environmental specifications and ECSS-E-ST-10-03C standard (Scaccabarozzi, D. et al., 2020, 2018). The FM has the same layout of the BB model for most subsystems. The geometry of elements such as mirror and lenses in 210 and 300 groups remained unchanged; however, a coating for UV protection was applied, where necessary. The mirror coating was in aluminum for the FM, instead of gold used for BB, guaranteeing a 99.7% reflectance efficiency. The laser and the photodiode were the same for the two models. Table 4 lists the components for both models. The differences between the two optical systems are due to the fiber, which is a 1-meter long commercial Thorlabs with an NA of 0.22 for the BB and a space qualified, 15-cm long, Optran WF fiber produced by Ceramoptec for the FM. The NA of the FM fiber was measured, obtaining a value of 0.27. Figure 14 shows the optical profile of the flight fiber (a) and of the Thorlabs fiber (b) during measurement of NA. The distance between fiber-sensor was 5.5 mm. The profile size was 3.097 mm (diameter) for Flight Fiber and 1.12 mm for BB fiber. The alignment procedures of the optical subsystems used for BB were applied for the FM using *ad hoc* tools as shown in figure 15. The internal dimensions of the intake system ducts were slightly modified to improve the sampling ability (Mongelluzzo, G. et al., 2019). The operation management board, instead, was completely different from the BB version. The two channels (Low and High) were still present, but the amplification factors were different and lower than those of the BB model.

Figure 16 shows the sampling volume profiles of the flight model (a) and the BB model (b). The two volumes are similar in dimension: 1.067 x 0.307 mm in FM and 1.036 x 0.351 mm in the BB model. The optical power is 117 mW for the FM and 130 mW for the BB model.

Considering the real parameters of the sampling volume (e.g. size, profile, optical power and the geometric configuration of the mirror, photodiode and position of the sampling volume), scattering simulations based on Mie theory were performed. These simulations are useful to quantify the current generated by the photodiode when hit by scattered light from a spherical calibrated particle. The theoretical data of the simulations were compared with the experimental data acquired (listed in table 3) with the BB model. Simulations based on Mie theory have also been performed for the FM and compared with the data acquired during instrument calibration. Figure 17 shows the comparison of the Mie curve with the experimental data for both models, showing that the experimental data are in good agreement with the theoretical curves both for the BB (red line) version and for the FM model (yellow line). For the FM, both the simulation result and the experimental data showed lower intensity values than for the BB model because of the different optical power. During the test phase, the laser of the BB model was powered at 198 mA, slightly below its maximum supply current equal to 200 mA. For the FM, instead, to increase the laser lifetime, it was chosen to lower the laser supply current to 166 mA. A notable difference between the data acquired by the two models lied with in error bars. The BB model showed greater error bars compared to the error bars of the FM because, during the measurements, the acquired signal was affected by environmental noise (the source of noise is unidentified) in the form of square and sine waves with variable amplitude and frequency. The noise also affected the average value of the acquired signals for the 0.400 µm and 1.076 µm diameter grains, resulting in an overestimation of their size.

In light of the problems encountered with the BB model, we applied both a physical RC filter on the management and acquisition board and a software filter capable of eliminating noise. The filter was specifically aimed to distinguish between the square waves and the true grain signal, automatically following the variations of the instrument noise level.

This led to a removal efficiency of the false positive detections of over 98%, without affecting the particles signals. Consequently, the experimental data acquired with FM showed a reduced uncertainty, properly fitting the theoretical curve.

# Summary and Conclusion

MicroMED, an optical particle counter capable of measuring size distribution and concentration of suspended dust present close to the surface in Martian atmosphere, was designed and selected to be accommodated in the next ExoMars space mission. The sensor is part of the Dust Complex suite, which was designed to the study of Martian dust and sand dynamics. MicroMED’s Flight Model is the result of a work that started with the development of two prototypes: the fluid dynamic model and the BreadBoard model. The development of the BB model and verification of its performance lays the foundation for performing for the first time, direct measurement of the size and concentration of suspended dust in the Martian atmosphere. All phases of the development of the BB and its subsystems contributed to the realization and optimization of the FM model. In fact, all the optical system alignment and performance verification procedures used for the BB were repeated for the FM.

Both the BB and the FM model consist of 3 subsystems, that have been tested and verified separately before being integrated into the prototype. The tested subsystems are: a) sampling system b) optical system and c) acquisition system. The representative fluid dynamic model of the sampling system was implemented to verify the suction capacity of dust in the range from 0.4 to 20 μm and the absence of turbulence; besides, it allowed the measurement of particle flow diameter. The experimental results confirmed that the sampling system is able to sample particles in the range of 0.4-20 μm without generating turbulences. The measured size of the gas flow is 1 mm in diameter in the sampling path.

The tests on the optical system allowed us to characterize it and fine-tuning the laser-300 group and optical fiber-210 group alignment procedures, which were then applied during the FM integration. The test results showed that the sampling volume has an elliptical shape, an optical power density of approximately 0.47 W/mm2, slightly higher than the minimum allowed value of 0.4 W / mm2, and a dimension of 1.036 mm x 0.360 mm. This last result ensures that most of the aspirated particles will pass through the sampling volume and will consequently be revealed.

The results of the tests carried out on the acquisition system confirmed the ability of the proximity electronics to amplify the signals by a factor of 105 for the Low channel and a factor of 107 for the High channel, without affecting the signal shape, up to frequencies of 2 MHz.

The BB model has been integrated and a proper testing campaign has been carried out in Martian simulated conditions, providing an instrument calibration curve.

The experimental points were compared with the theoretical curve calculated by simulations based on Mie theory. The comparison shows that there is a good agreement between the experimental data and the theoretical curve.

The same tests have been performed with the FM model. A notable difference between the data acquired by the two models lies in the error bars, which for the BB model are greater than for the FM, despite the BB sampling volume being more uniform. This occurred because the acquired signal of BB was affected by environmental noise, in particular square and sine waves with variable amplitude and frequency were observed.

Mindful of the problems experienced with the BB, we have applied a physical RC filter on the management and acquisition board and a software filter, to eliminate the environmental noise. The latest modifications applied have further improved the performances of the flight model.

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([fabio.cozzolino@inaf.it](mailto:fabio.cozzolino@inaf.it)).

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