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MiLi Project, Thermo-Mechanical design of a miniaturized LiDAR for Mars advanced atmospheric research

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Abstract

In this work, the thermo-mechanical design of MiLi (Miniaturized LiDAR for Mars Advanced Atmospheric Research) is described, addressing the design challenges posed by the Martian environment. Atmospheric LiDARs could be used to examine atmospheric dust and ice-based clouds on Mars, but typically those instruments are heavy and defined by a high-power consumption, therefore less attractive as pay-loads for landers and rovers. The EU-funded MiLi project aims to close this gap, designing a compact, low-power LiDAR that will provide a precise characterization of the suspended dust and clouds in the Martian atmosphere.

MiLi proposes to higher the TRL of three basic technologies to enable the construction of the miniaturized LiDAR for the Mars atmospheric research, i.e. the semiconductor lasers and new Si-PMTs (Silicon Photomultipliers) detectors, free-form optical technology, and low CTE materials. The target mass is 6 kg, and the overall power consumption less than 15W. The instrument should be moreover capable of surviving and operating at very low atmospheric temperatures, to minimize the requirements for its accommodation in any lander/rover.

The thermo-mechanical feasibility study encompasses the design requirements, materials selection, and evaluation of different design solutions to ensure the instrument's performance and survival in these extreme conditions, allowing the definition of the instrument's mechanical architecture. Overall design strategy was based on the trade-off between the mass budget and the instrument performance. Validation of the mechanical resistance and thermal design requirements fulfilment was performed by developing finite element models of the main instrument components, designed by using numerical quasi-static, modal, and thermo-elastic analyses. The major result of the research is the detailed instrument design posing the basis for the subsequent project phases, i.e. the manufacturing of an instrument mock-up and testing in representative environmental conditions.

Keywords: MiLi; Atmospheric LiDAR; Thermomechanical design; Mars.

Nomenclature

E - Young's Modulus
ρ - Density
ν - Poisson's Ratio
λ - Thermal Conductivity
σ_{LIM} – Maximum Allowable Stress

Acronyms/Abbreviations

LiDAR - Light Detection and Ranging
PBC - Particle Backscatter Coefficient
PLDR - Particle Linear Depolarization Ratio
LR - LiDAR Ratio
CR - Color Ratio
CTE - Coefficient of Thermal Expansion
FEA - Finite Element Analysis
VM - Von Mises
TRL - Technology Readiness Level
INTA - Instituto Nacional de Técnica Aeroespacial
DLR - Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
IAC - International Astronautical Congress
MiLi - Miniaturized LiDAR for Mars Advanced Atmospheric Research
Si-PMT - Silicon Photomultipliers
CALIPSO - Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observation
MOLA - Mars Orbiter Laser Altimeter
LIM - Limit

1. Introduction

An atmospheric LiDAR is a specialized type of LiDAR (Light Detection and Ranging) system used to study and monitor the atmosphere. It works by sending laser light pulses into the atmosphere and measuring the

time it takes for the reflected or scattered light to return from particles and molecules in the air. This time provides information about the distance to the target (clouds, layer of dust, etc.). This technique ac offers detailed information about atmospheric properties, such as the concentration and distribution of aerosols, dust particles, smoke, pollutants, and clouds, as well as features like wind speed and direction, by measuring different properties of the scattered light, such as intensity, polarisation, or wavelength [1-4]. These properties are crucial for understanding the atmospheric composition, dynamics, and potential for life. Although some LiDARs have already been launched to analyse the Martian atmosphere, the majority have been deployed remotely (e.g. MOLA and CALIPSO) [5-7]. The Phoenix LiDAR is the sole instance of an atmospheric LiDAR operating in situ on Mars's surface [8-9]. It was equipped with a two-wavelength configuration, and it was developed with an overall mass of 6 kg and a power budget of up to 30 W. Indeed, thanks to the unique performance of those instruments, LiDARs are constantly under development for space and planetary applications.

Other proposals for miniaturized Mars LiDARs exist, but they exhibit limited range and functionalities [10-11]. The Miniaturized LiDAR for Mars Advanced Atmospheric Research project seeks to mature several key technologies to enable the miniaturization and low power of future Martian atmospheric LiDAR. By achieving these technical milestones, MiLi aspires to contribute to the precise characterization of Martian atmospheric phenomena, including dust cycles and cloud formation patterns [12-13]. These contributions are anticipated to advance our comprehension of the Martian climate.

Therefore, the main engineering goal of the MiLi project is to increase the Technology Readiness Level (TRL) of the base technologies that will enable the construction of the miniaturized, low-powered LiDAR for Mars atmospheric research. These technologies are related to the usage of structures with controlled coefficients of thermal expansion and new ceramic materials, which can provide benefits to the thermal design of the instrument, the development of miniaturized laser modules, to be used in the emitter channels, and the integration of free-form optics within the optical layout of the instrument.

2. Instrument description

2.1 MiLi's design challenges

An atmospheric LiDAR must be capable of detecting the extremely weak signal of light backscattered by particles and molecules in the atmosphere (which we will call the LiDAR signal). Therefore, the first challenge is being able to count photons. The LiDAR signal backscattered from the farthest layers of the atmosphere, tens of kilometres away, requires the ability to count photons one by one. However, the signal from the lower layers is several orders of magnitude stronger, and the detector must be able to operate in a configuration we call analogue mode, where hundreds or even thousands of photons are arriving simultaneously. The situation becomes even more complex when this needs to be done without daylight (from the sun and diffuse skylight) masking this weak signal or even saturating the detection system.

The challenges above—weak signal, large dynamic range, and strong ambient light—are what define the design of a LiDAR system. To make it work, the design must focus on the following key points:

- Use detectors with a wide dynamic range that are even capable of photon counting.
- Use a large-aperture telescope to collect more light, but not so large that it becomes too heavy.
- The telescope must have a very narrow field of view (FoV) to prevent sunlight and diffuse skylight from reaching the detector, introducing noise, or even saturating it.
- Use optical filters with very narrow spectral ranges so that only light from the excitation source, which must be monochromatic, reaches the detector.
- Use a powerful, monochromatic, and collimated light source with low divergence that fits entirely within the telescope's FoV. A laser meets these three requirements.

Some of these point requirements conflict with making the LiDAR system small and low power. As a result, the receiving telescope cannot be as large as desired, and the laser collimation systems cannot grow too large. To generate the light pulses, not just any laser can be used; it must be small, lightweight, and low in power consumption. Other of these points have a direct impact on the LiDAR's thermo-mechanical design. Key points include ensuring the alignment between the emitter and receiver is maintained, as they have a very narrow FoV and divergence, small deformations due to thermal expansion could result in a loss of alignment. Maintaining the correct distances between optical elements in the collimators is also critical to preserve the necessary low divergence. Similarly, the receiver's FoV must remain stable with temperature, keeping the optical elements positioned according to the needs at each temperature. Another temperature-related aspect that needs to be controlled is the optical filter and the laser. The spectral response of both components shifts with temperature, potentially causing a mismatch between the laser and the filter.

For all these reasons, traditional LiDAR systems usually have active thermal stabilization to keep the entire instrument at a consistent temperature. This adds weight and increases power consumption. One of MiLi's design goals is to create a system that can function well without active thermal control, except for a few key elements where it cannot be avoided.

2.2 Instrument requirements

The MiLi has been designed to accomplish a set of requirements from mechanical, optical, thermal, and operational considerations. MiLi is not designed yet for any specific mission, but the requirements have been assumed considering general space conditions [14-17]. These requirements guarantee that the instrument will operate as expected facing the harsh Martian environment.

The mechanical subsystem is designed to support and encapsulate the instrument's components, ensuring:

- Structural Integrity: it must be a robust, integrated unit for ease of handling, with no need to disassemble the emitter and receiver telescopes.
- Mass budget: the total mass must be under 6 kg, consistent with the mission's mass constraints.
- Dynamic behaviour: MiLi must withstand launch vibrations, with the first vibration mode exceeding 150 Hz.
- Quasi-static loading: the design must endure quasi-static loads of up to 100 times the gravitational acceleration, ensuring stability under extreme conditions.
- Thermal scenario: The subsystem must operate within interface temperature at 40°C and environmental temperature at -40°C, simulating cold case scenario on Mars.

The optical subsystem, crucial to the LiDAR's scientific objectives, must meet the following:

- Dual-Wavelength Operation: It must handle two wavelengths for Particle Backscatter Coefficient (PBC) and depolarization ratio measurements, for dust and cloud analysis.
- High-Resolution Detection: The receiver, featuring a large-capacity telescope, must ensure high-resolution detection across both wavelengths for detailed vertical profiling.

Operationally, the MiLi must meet:

- Power Efficiency: power consumption must not exceed 15W, adhering to the lander or rover's energy budget.
- Autonomy and Reliability: the instrument must operate reliably and autonomously, adapting to Mars' unpredictable environment.

2.3 Optical layout

The optical system for the MiLi LiDAR employs a '2β+1δ' configuration, specifically designed to enhance the characterization of Martian dust and clouds. This configuration allows for the determination of the Particle Backscatter Coefficient (PBC) at two distinct wavelengths (2β) and the depolarization ratio at one of those wavelengths (1δ). These measurements are critical for deriving three key LiDAR parameters: the particle linear depolarization ratio (PLDR), the LiDAR ratio (LR), and the colour ratio (CR).

This advanced LiDAR configuration contributes significantly to our understanding of Martian atmospheric particles by providing detailed insights into several important characteristics. It enables the identification of particle types (dust or cloud), assessment of aerosol shape (particle asphericity), determination of particle size (fine-mode fraction), evaluation of dust opacity, quantification of ice content in clouds, and exploration of interactions between dust and clouds. Importantly, all this data can be obtained with vertical resolution, representing a substantial improvement with respect to other LiDARs [18-19] over the current columnar measurement techniques employed in Martian atmospheric studies [20].

To meet these scientific objectives, the optical system is divided into two primary subsystems: the emitter and the receiver. The emitter projects two distinct wavelengths into the Martian atmosphere and is further divided into two channels, each corresponding to one of the selected wavelengths. The receiver, on the other hand, captures the backscattered LiDAR signals and transmits them to the detection system. The receiver includes a telescope with a high light-collecting capacity, along with two channels designed to separately capture the signals at each of the emitted wavelengths.

The optical layout of MiLi plays a crucial role in the overall thermo-mechanical design of the instrument. As part of the ongoing design iterations, significant efforts have been made to minimise the instrument's size and mass, which are critical for space missions.

a. Receiver unit

Figure 1 shows the receiver's primary components: a collector unit (telescope) and two optical chains optimised for visible and infrared wavelengths.

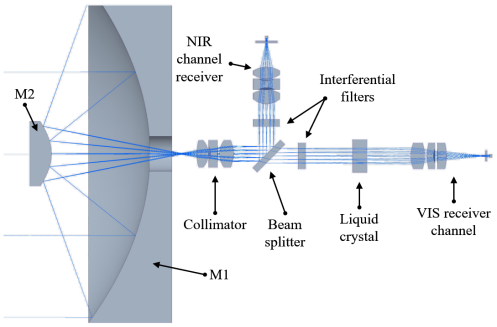

Fig. 1. Optical layout of the receiver unit: optical elements and the expected raytracing are shown.

b. Emitter unit

To operate the instrument in its dual-wavelength configuration, the MiLi requires the integration of two distinct emitters. While the emitter for the visible spectrum has been clearly defined, the selection of the infrared emitter remains a critical decision point, necessitating a choice among three potential configurations. These options are represented comparatively in Figure 2, compared as a function of the full divergence from 0.1° to 0.05°. Each of the three proposed configurations for the infrared emitter presents a distinct set of trade-offs in terms of scientific performance and the overall mass budget of the instrument. From a mechanical design perspective, the most compact configuration offers considerable advantages, particularly in terms of mass reduction and enhanced structural stability. However, this alteration in emitter architecture necessitates a comprehensive trade-off analysis to achieve an optimal balance between performance requirements and the imposition of rigorous mass constraints. To address these considerations, a series of feasibility studies have been conducted to assess the impact of each emitter configuration on the overall system design, as illustrated in Figure 3.

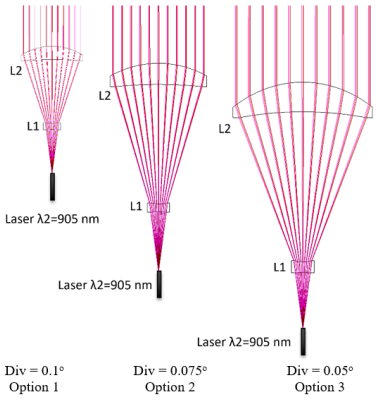

Fig. 2. Suggested emitter optical layout configurations.

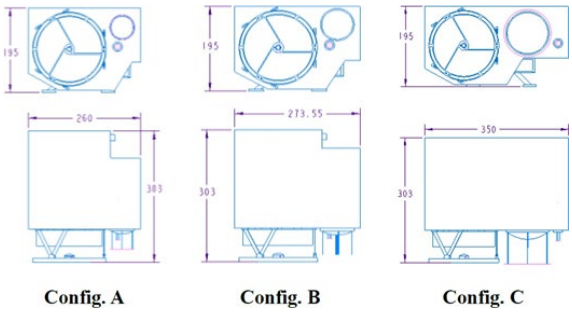

Fig. 3. A comparison of the dimensions of three LiDAR configurations.

The second emitter type was identified as the best compromise between scientific performance and mass budget. Accordingly, the MiLi design was based on the selected emitter architecture, incorporating its specifications into the overall instrument design.

3. Thermo-mechanical design

3.1 Materials selection

The selection of materials for the MiLi was performed focusing on selecting those that have been extensively utilized in space-related applications. These include titanium and aluminium alloys, which have demonstrated their efficacy in analogous scenarios.

Furthermore, the project investigated the usage of advanced silicon carbide materials, developed by a consortium partner, due to their tuneable coefficient of thermal expansion (CTE), which offers potential benefits for the instrument's thermal management. In addition to metals, low-outgassing polymers have been considered during the detailed design phases to ensure minimal contamination and optimal performance in the Martian environment. A summary of the key properties of these materials can be found in Table I.

3.2 Structural overview

The overall design approach was established during the Feasibility Study conducted at DLR Bremen, leading to a successful demonstration of the design.

Table 1. Materials' mechanical and thermal properties

	Invar36	Ti_6Al_4V	Al7075	Vespel SP1	LAS-SiC
E [GPa]	148	113.8	71.7	2.413	120
ρ [kg/m^3]	8050	4430	2810	1430	2590
ν	0.23	0.342	0.33	0.33	0.23
CTE [µm/(m°C)]	1.3	8.6	23.6	54	-0.18
λ [W/(m°C)]	10.15	6.7	173	0.35	n.a.
σ_{LIM} [MPa]	483	880	503	86.2	150

feasibility [21], but the detailed design required structural optimization carried out to fulfil the challenging design requirements.
The MiLi architecture is shown in Figure 4 and described in the following.

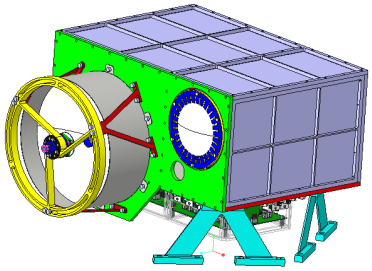

Fig. 4. MiLi 3D model.

The MiLi is comprised of seven principal structural groups. *Group 100* comprises the components required to support the M1 and M2 mirrors within the receiver unit. One key element of the group is the holder of mirror M2, designed with LaS-SiC low CTE material to provide the required optical stability within the expected temperature working range. Moreover, the group holds a barrel designed to mount the focusing lenses, to ensure precise alignment and stability of the optical elements within the system.

Group 200 comprises the essential components of the receiver's optical pathway. This includes the beam splitter box, which divides the received beam (scattered light from the observed medium), and the associated lens arms that direct the split beams towards the detectors. Furthermore, the group incorporates a liquid crystal element, which plays a significant role in modulating the beam before it reaches the detectors.

Group 300 and *Group 400* boards are responsible for processing the signals received from the detectors and coordinating the various subsystems. The boards are housed in boxes designed to minimize the mass budget but at the same time, assure electromagnetic interference shielding.

Group 500 holds the visible laser of MiLi: the group comprises an optical barrel designed to provide all the required degree of freedom and movements to achieve the optical alignment, and the thermal management of the laser and its electronics within the designed operating temperature range.

Group 600 comprises the second laser operating within the infrared spectrum. The laser is mounted on an optical barrel that provides support for the attachment of the main lenses and required movements for the optical alignment. Moreover, a thermal strap and thermoelectric element are integrated into the group to manage the operation of the laser within the thermal working environment.

Eventually, *Group 700* comprises the main structural parts of the MiLi. This encompasses the optical bench, which serves as the foundation for the optical components, covers both the emitter and receiver units, and the supporting tripods. This group provides the structural integrity of the overall instrument and components. Figure 5 shows a graphical view of the MiLi's group and mechanical architecture.

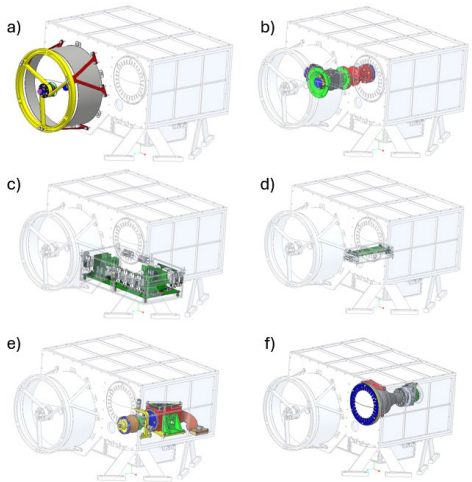

Fig. 5. MiLi's groups view, a) Group 100, b) Group 200, c) Group 300, d) Group 400, e) Group 500 and f) Group 600.

3.2 MiLi FE model and numerical analyses

The design was guided by numerical finite element (FE) quasi-static and modal analyses, to ensure mechanical robustness within the expected working thermal and mechanical environments. A 3D finite element model of MiLi was developed. The model comprises about 6837 triangular and 2386 quadrilateral shell elements and 207880 tetrahedral elements. The meshed 3D model is shown in Figure 6. Indeed, lenses and main components were modelled as lumped masses to accurately capture inertial effects but reduce the computational effort.

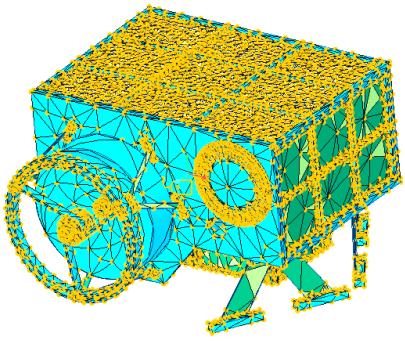

Fig. 6. Isometric view of the MiLi FE meshed model.

3.3 Quasi-static analyses

The resulting Von Mises stress distribution and corresponding displacements are illustrated in Figure 7.

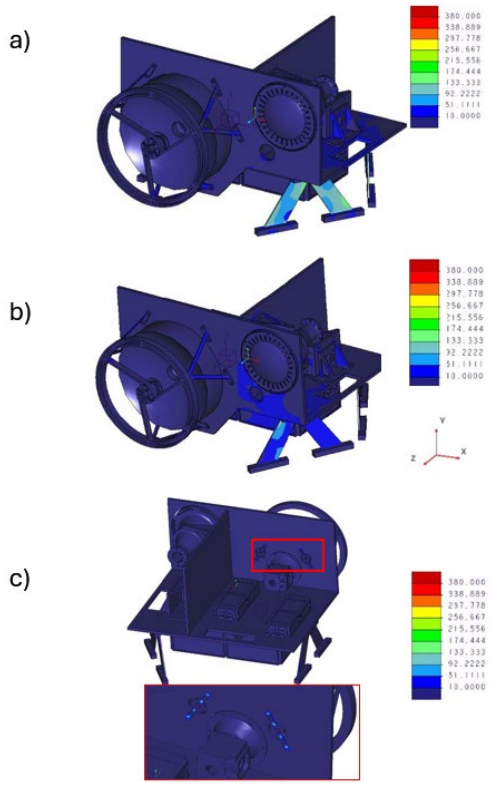

Fig. 7. Results of the quasi-static analyses: a) VM stress distribution due to 100g at the X direction, b) VM stress distribution due to 100g at the Y direction, and c) VM stress distribution due to 100g at the Z direction. Units are MPa.

3.4 Modal analysis

The modal analysis identified the first four modes of vibration of the MiLi, as shown in Figure 8. Computed natural frequencies are summarized in Table 2.

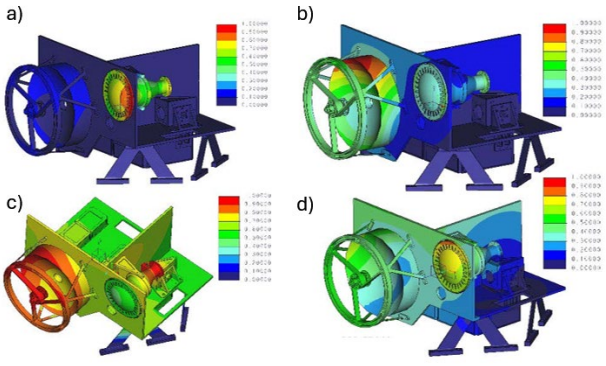

Fig. 8. Results of the FE modal analyses: a) first mode, b) second mode, c) third mode and d) fourth mode of vibration.

Table 2. Computed modes of vibration - MiLi

Mode number	Natural frequency (Hz)
1	215.5
2	239.1
3	246.4
4	332.6

3.5 Thermal analysis

The thermal analysis was performed considering mounting interface temperature at 20°C, and radiative environment at -80°C, without any convective heat dissipation. The heat power budget for MiLi comprises 25W for the visible laser, 1.2W for the IR laser, and 2W for the front end and main electronics. The heat dissipation strategy exploits a passive radiative radiator (400x200 mm size) with an emissivity of 0.9. The computed temperature distribution is shown in Figure 9.

3.6 Discussion

Quasi-static analyses allowed verification of the mechanical resistance of the main components, in particular, the stress state over the bipods and the supporting structures of mirror M1 provided acceptable margins of safety versus the admissible condition. As shown in the quasi-static analysis results, VM maximum stress was always below the admissible limits, providing a margin of safety of about 1.5. Moreover, the forcing along the X and Y directions resulted in a larger stress on the instrument bipods, whereas the stress state increased when the loading was applied in the vertical direction on the flexures supporting M1.

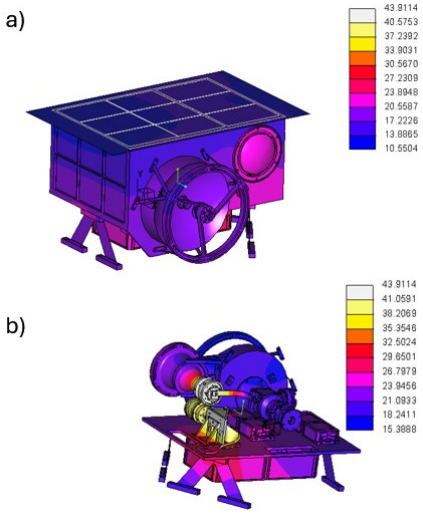

Fig. 9. Thermal analysis result: a) MiLi temperature distribution and b) detailed view of the internal temperature distribution.

Computed modes of vibration show a dynamic behaviour compliant with the dynamic requirement, i.e. the first modes are above the 150 Hz limit condition. The first two modes are related to the IR emitter group and the holding structure of the M1 mirror, at about 216 Hz and 239 Hz. The first mode which involves the compliance of the MiLi's supporting bipods is at 246 Hz, fully compliant with the design requirement.

Eventually, the thermal analysis showed that the proposed radiator size allows dissipation of the overall power expected from the heat budget. The computed mass increase of the radiator solution has been evaluated to be within 250 g, and part of this mass can be taken from the actual one used for the top cover of the instrument.

4. Conclusions

This work describes the thermo-mechanical design of MiLi, a miniaturized two-wavelength LiDAR designed for advanced atmospheric research on Mars.

The instrument design was based on numerical analyses to assess the instrument's structural and thermal theoretical performance. The obtained results confirmed that the proposed thermo-mechanical architecture withstands the design loads, providing acceptable performance in the expected mechanical and thermal working scenarios. Furthermore, the possibility of integrating low CTE materials for some critical components of the instrument established a robust foundation for MiLi's further development.

Future work will focus on further refining the thermo-mechanical design, including additional structural optimization and trade-off analyses and the characterization of a mockup of the instrument, to assess the instrument performance in a representative environment and validate the performed design.

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