Feasibility design of MiLi, a miniaturized lidar for Mars observation

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Abstract—**This work describes the feasibility design of MiLi, a miniaturized lidar under development to operate on Mars. Atmospheric lidars could be employed to study atmospheric dust and ice-based clouds, but typically those types of instruments exhibit considerable mass and are characterized by high power consumption, so they cannot be easily retrofitted aboard landers. The MiLi project, funded by the European Union, aims to develop a compact, lightweight lidar for detailed atmospheric analysis of the Red Planet. The development of this instrument, which seeks to overcome the typical limitations of lidars, may increase the availability of this type of remote sensing technology in the context of planetary missions and wants to deliver precise characterization of Martian atmospheric dust and ice-based clouds. The feasibility study encompasses the design requirements, material selection, and evaluation of different design configurations to ensure the instrument's performance and survival in extreme conditions, posing the basis for the development of the instrument's mechanical architecture. Overall design procedure was based on the trade-off between the mass budget and the instrument performances. Assessment of the mechanical resistance was performed by using quasi-static and modal numerical analyses.**

Keywords — MiLi, Atmospheric lidar; Thermomechanical design; Mars; Feasibility study

I. Introduction

This work provides the feasibility of miniaturizing lidar technology for space applications, particularly for Mars exploration. Lidar (light detection and ranging) is a method of measuring the time-of-flight of a transmitted pulse from the instrument to the target and back [1-2]. Lidar technology has unique capabilities to perform atmospheric research studies, in particular, to measure aerosol particles [3-4]. Even though these properties may be crucial for understanding the atmospheric composition, dynamics, and potential for life, they are constantly under development for space and planetary applications [5]. Existing commercial lidars are generally massive instruments and require a large power budget to operate. Moreover, the space environment poses some challenges to be faced, with high vibration levels and loadings expected at the launch and wide temperature ranges to be overcome. The *Miniaturized Lidar for MARS Advanced Atmospheric Research* (MiLi) project aims to explore the possibility of using lidar technology to miniaturize the overall instrument, minimizing the required power budget while operating during the daytime for Martian atmospheric studies.

Although some lidars have already been launched to analyze the Martian atmosphere, most have done so remotely (e.g. MOLA and CALIPSO) [6-7]. Thus far, the Phoenix lidar is the only example of an atmospheric lidar operating in situ on Mars's surface [8-16]. It had a two-wavelength configuration, 6 kg mass and an overall power budget of 30 W. Other proposals for miniaturized Mars lidars exist (e.g., IKI's MetNet Lander LIDAR), but they have limited range and functionality.

The MiLi project is funded by the European Commission, and it is a collaborative effort of a group of Research Institutes and Companies led by INTA (National Institute of Aerospace Technology). The project aims to design a miniaturized lidar leveraging on different innovative aspects to be addressed and developed:

- new ceramic materials with a controlled coefficient of thermal expansion, to achieve an athermal design increasing the passive working temperature range; and
- use of miniaturized and efficient laser modules; and
- free-form optics-based solutions for the optical design, to increase the compactness of the overall instrument.

Section II provides an overview of the general design requirements, methods, and preliminary optical layouts, whereas Section III describes the numerical results of the feasibility analyses as well as future activities foreseen for the development of MiLi. Eventually, Section IV summarizes the findings, concluding the paper.

II. Materials and Methods

A. Design requirements

MiLi design is not related yet to any mission, but the thermo-mechanical requirements have been assumed considering general space conditions. In particular, the operating temperature range should be between -80°C and 40°C, considering a "general" Martian cold case without a power budget to stabilize in temperature of the instrument optics. Concerning the mechanical requirements, the minimum structural resonance should be over 150 Hz, to avoid critical coupling with the sweep sine excitation at the launch. Finally, considering quasi-static loading of 100 times the Earth's gravitational acceleration would allow guiding the mechanical design phase and the subsequent mechanical resistance assessment. Moreover, the mass budget for the whole instrument should not exceed 6 kg and the operational power consumption should be less than 15W.

Selected materials have been chosen among typical metals (i.e., titanium and aluminium alloys) with documented space heritage, whose assumed properties are summarized in Table I. However, as a result of the project, the usage of new silicon carbide materials will be investigated, manufactured and developed by one partner of the project Consortium, thanks to the tunable Coefficient of Thermal Expansion (CTE). Besides metals, low-outgassing plastics will be selected in the detailed design phases of the project.

TABLE I. MATERIALS' MECHANICAL AND THERMAL PROPERTIES

	Invar 36	**Ti6Al4V**	**Al7075**
E [GPa]	148	113.8	71.7
ρ [kg/m^3]	8050	4430	2810
ν	0.23	0.342	0.33
CTE [μm/(m°C]	1.3	8.6	2.36
λ [W/(m°C)]	10.15	6.7	173
σ_{LIM} [MPa]	483	880	503

B. Optical layouts comparison – mass budget comparison

The MiLi optical layout serves as a crucial input for its thermo-mechanical design. The general architecture of the instrument comprises an emitter unit, holding two lasers at different wavelengths, in the visible (VIS) and Near-InfraRed (NIR) ranges, and a receiver unit, which measures the backscattered lights from the investigated medium. The optical layout's initial versions had a mass of about 5.6 kg, but during a Concurrent Design Facility (CDF) study, executed at the German Space Agency (DLR) in Bremen, the overall target mass was reduced.

Figure 1 illustrates the comparison of the two optical layouts, focusing on the receiver part. Figure 2 shows a detailed/section view of the selected layout and its primary components, highlighting the major collector unit (telescope) and two optical chains for VIS and NIR wavelengths.

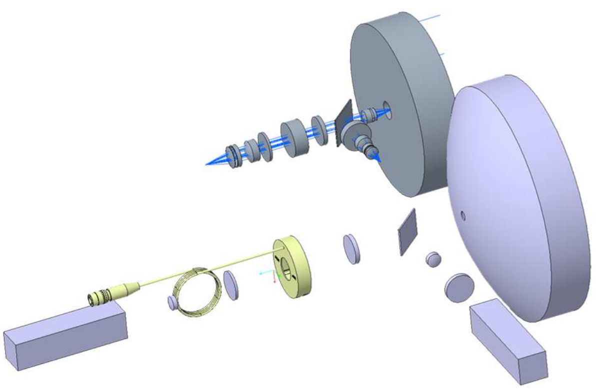


Fig. 1. View of two receiver optical layouts, the smaller being the output from the CDF study.

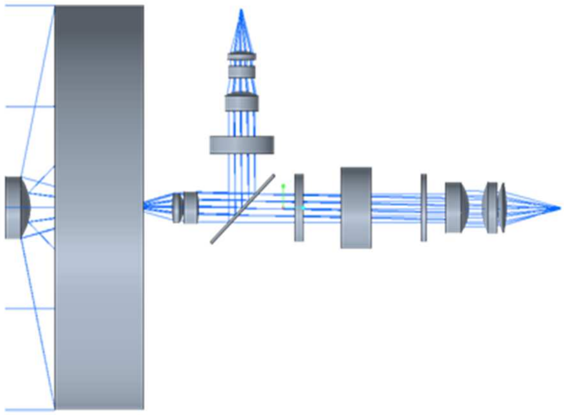


Fig. 2. Cross-section view of the selected optical layout for the receiver unit (selected configuration after the CDF study).

To proceed and evaluate the instrument's feasibility, it was necessary to estimate the raw mass budget. The latter activity results are presented in Table II.

TABLE II. MASS ESTIMATION OF THE INSTRUMENT (CDF STUDY)

Group	**Mass [g]**	**Mass with margin [g]**
Optics	2308	-n.d.
Electronics	193	273
Mechanics:		
Optical bench	800	960
Bipods	900	1080
Electronics enclosure	350	420
Lens supports	720	864
Total	5271	5905

As shown in Table II, the overall mass budget is expected to be within the requirement. The largest part of the budget is related to the structural parts to hold the optics, about 44% of the budget, and the electronics.

A 3D view of the MiLi assembly as a result of the CDF study is shown in Figure 3. Aluminium alloy was chosen to estimate the structures and the supporting elements of the optics mass, whereas the major optical elements were modelled with Invar 36 material. Finally, titanium bipods were selected to provide thermal insulation for the MiLi instrument with respect to the mounting interface on the spacecraft.

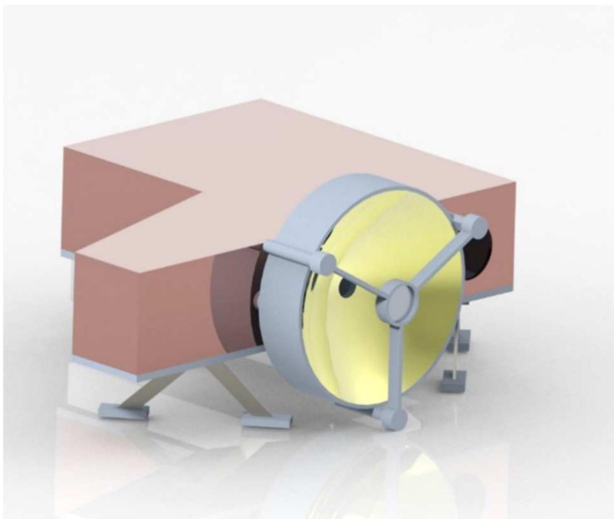


Fig. 3. CAD model of the MiLi assembly – feasibility CDF study.

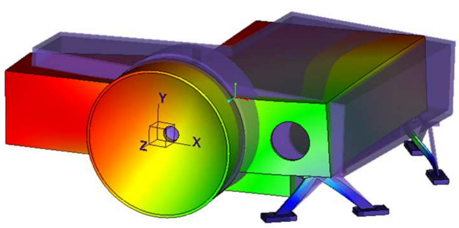
C. Methodology

The following numerical analyses were performed to assess the feasibility of the MiLi. In particular, modal analyses were planned to explore the dynamic behaviour of the instrument, focusing on the frequency range where sweep sine and random excitation are present at the launcher take-off. As previously said, the major result is to guarantee that the first structural mode of vibration is above the 150 Hz requirement, to avoid any critical coupling with high vibration levels of the launcher excitation. Moreover, quasi-static analyses were performed as well, considering a quasi-static acceleration of 100 times the Earth's gravity. The design load was derived from previous projects [17-20], accounting for the impact on Mars. The quasi-static analyses, encompassing the estimation of a safety factor from the Von Mises stress measure, allow for assessing the mechanical resistance and assuring the instrument's functionality.

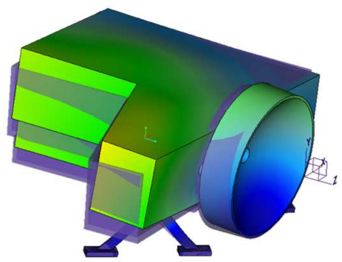
III. NUMERICAL RESULTS

A. Modal analyses

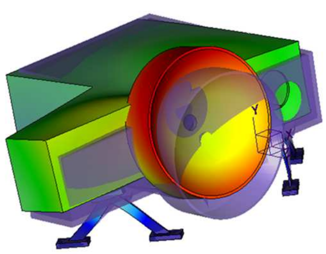
The first three modes of vibration computed on the MiLi assembly Finite Element Model (FEM) are shown in Figure 3.



First mode – 337 Hz



Second mode – 367 Hz



Third mode – 460 Hz

Fig. 4. Modal analysis results. The first three modes of vibration with overlayed undeformed configuration (purple colour).

The reference system of the MiLi is shown as well. The first mode of vibration is related to the rigid movement in the horizontal plane of the optical bench, one of the main structural components, over the supporting structures. The movement involves the deformation of the bipods, whereas the optical bench acts as a rigid body. The first resonance was found to be at about 340 Hz, providing a margin of safety of about 2 with respect to the dynamic requirement. The higher modes still show a similar general rigid movement (i.e., in the X-Y plane) of the optical bench on the bipods, testifying to a general structural rigidity of the MiLi assembly.

B. Quasi-static analyses

The analyses were performed by applying a static acceleration of 100 times the Earth's gravity along X, Y, and Z directions. The worst-case result is shown in Figure 5, where the computed stress state with the load along the Z-axis is shown. The worst case highlighted a maximum Von Mises stress at the bipod of about 257 MPa, providing a safety factor (computed as the ratio between the material yield stress and the maximum stress) of about 3.4 with respect to the limit condition. All the values of maximum stress showed acceptable results, therefore ensuring the structural integrity of the MiLi assembly.

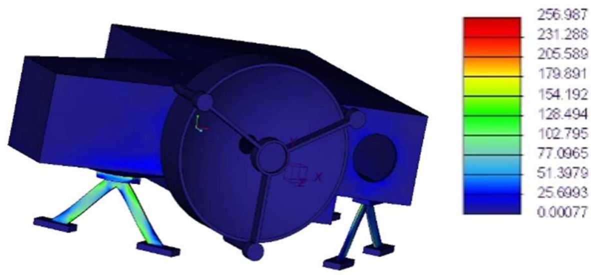


Fig. 5. Quasi-static analysis loading the assembly along the Z-axis. The Von Mises stresses distribution (units in MPa).

C. Achieved results and ongoing activities

Based on the obtained results, the feasibility design of a miniaturized lidar was partially demonstrated, assessing both the dynamic and mechanical performance of the proposed design. The result was achieved by fulfilling one of the most stringent requirements, i.e., the mass budget. Moreover, optical design optimization is ongoing, allowing the optimization of the instrument performance. For instance, with regard to the emitters' optical configuration, different options for the NIR emitter are under investigation, to find the tradeoff between the mass budget and the scientific requirements. A comparison between the studied configurations is shown in Figure 6. The three proposed solutions are characterized by different optical performances (i.e. optical divergence) and mass budgets. The lower the envelope, the smaller the divergence. The selection of the intermediate configuration (option 2 in Figure 6) seems to be the solution to accommodate both the highlighted needs.

However, a more detailed evaluation of the proposed options would be necessary in the next phases of the instrument development.

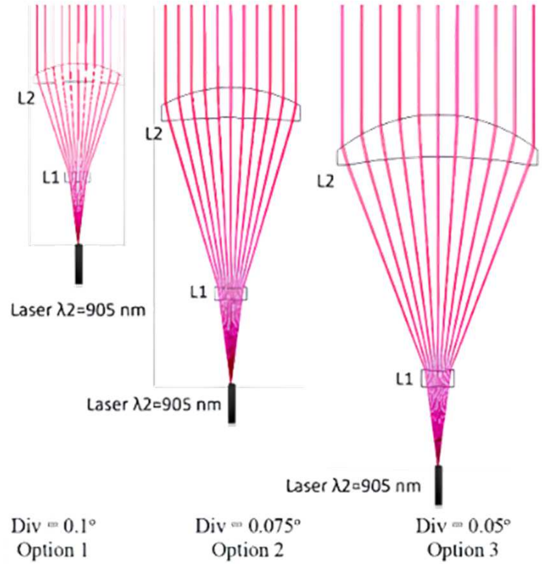


Fig. 6. Studied NIR emitter optical layout configurations.

The result is interesting and promising but can be further refined, considering that structural optimization is foreseen to be exploited as a future activity within the project framework, aiming to minimize the mass budget and at the same time, fulfil the other stringent requirements, i.e. the operative temperature range and the consumption power budget.

These tasks will be tackled by exploiting innovative structural and thermal design solutions, e.g. based on non-conventional design methodologies, performing optical layout optimization, implementing state-of-the-art optical manufacturing techniques, and exploring new materials, thanks to the effort of the MiLi project Consortium.

IV. Conclusions

This work describes the preliminary feasibility design of MiLi, a miniaturized lidar for advanced atmospheric research on Mars. The paper describes the general architecture of the instrument, the goals and objectives of the project, and summarizes the results of the performed numerical analyses that allowed the verification of the dynamic and quasi-static behaviour and provided the general feasibility of the whole instrument. Indeed, modal analyses confirmed that required structural rigidity can be achieved within the intended mass budget, providing a consistent margin of safety with respect to the lowest frequency acceptable eigenmode. Moreover, the Von Mises stress state on the structural elements supporting the bench is below the acceptable limit. Further structural and thermomechanical development and optimizations are planned as the next steps of the research activities, besides comparative analyses on achievable performance based on different optical layouts and trade-off analyses between optical, scientific and mechanical requirements and goals.

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