# M-DLS laser and heterodyne IR spectrometer for studies of the Martian atmosphere from ExoMars-2018 landing platform

Alexander V. Rodin*[a], Imant I. Vinogradov[b], Victor V. Barke[a], Artem Yu. Klimchuk[a], Oleg V. Benderov[a], Vladimir M. Semenov[a], Yury V. Lebedev[a], Dmitry V. Churbanov[a], Maxim V. Spiridonov, Anastassia A. Pereslavtseva[a], Igor V. Skripachev[d]
[a]Moscow Institute of Physics and Technology, 9 Institutsky Pereulok, 141700 Dolgoprudny, MO, Russia; [b]Space Research Institute, Profsoyuznaya 84/32, 117997 Moscow, Russia; [c]Prokhorov General Physics Institute, Vavilova 38, 119991 Moscow, Russia; [d]High Purity Substance Institute, Tropinina 49, 603950 Nizhniy Novgorod, Russia;

## ABSTRACT

A compact, lightweight multichannel laser and heterodyne spectrometer is under development for the ExoMars-2018 landng platform. The instrument is aimed at sensitive measurements of the ambient atmosphere composition, isotopic ratios and structure, both in situ and on the open path by direct Sun observations.

**Keywords:** Mars, laser spectrometer, heterodyning, Mars atmospheric composition, Doppler wind measurements

## INTRODUCTION

Minor components of the Martian atmosphere is one of the major scientific goals of the joint ESA-Roskosmos ExoMars mission. Remote sensing of the Martian atmosphere from the orbiter, including methane and other minor species, is a primary focus of the TGO orbiter[1] to be launched in 2016. The second launch should carry the Pasteur rover[2] and the landing platform, which, after facilitating rover delivery to the planet's surface, is expected to operate as a self-consistent lander during one Martian year. The platform will carry a limited set of science payload, including meteo complex, spectrometers, mass spectrometer, gas chromatograph, dust suite, electromagnetic sensors. Scientific goals of the experiments onboard ExoMars platform are related to detailed studies of the atmospheric environment, with little attention being paid to surface science. This paper describes one of those experiments, the Martian Diode Laser Spectrometer (M-DLS).

Diode laser spectroscopy (DLS) is known as an efficient technique in gas analysis, where high sensitivity and accuracy are required. In its classical implementation, DLS is based on laser radiation absorption measurement in a cell filled by a gas sample of the ambient atmosphere[3]. Specially designed distributed feedback (DFB) lasers are used for DLS applications, with narrow emission bandwith (typically less than few MHz) and emission wavelength control capability via temperature, in turn affecting built in distributed resonator dimension, and pump current, which charge carrier concentration and hence, resonance frequency. While laser radiation passed through a gas sample is modulated in frequency, transmission spectrum in characteristic near-infrared (NIR) absorption features could be measured. Frequency sweeping range of ~1 $cm^{-1}$ and an unprecedented spectral resolution determined by the sounding laser bandwidth and reaching $\lambda/\delta\lambda \sim 10^8$, provide detection and accurate concentration measurement for most abundant components of the Martian atmosphere and their isotopes.

Not only tunable diode lasers can be used to analyze gas absorption spectra in a local atmosphere, but also as local oscillators (LO) in a heterodyne spectro-radiometer[4]. With direct Sun observation geometry, heterodyne spectroscopy in the near-infrared spectral range provides high spectral resolution, extended optical path comparable with the atmospheric scale height, and spectral measurement accuracy limited by shot noise. In addition to sensitive measurements of atmospheric molecular and isotopic composition, unique capabilities of the heterodyne spectro-radiometry include vertical profiling of minor components and Doppler wind measurements. The instrument will take advantage of

*alexander.rodin@phystech.edu; phone 7 498 744-6524; http://planetsatmo.fizteh.ru

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heterodyne spectroscopy in both NIR and MIR spectral ranges in order to obtain the first ever measurements of water vapor, methane, carbon monoxide and wind vertical profiles in the lower scale height of the Martian atmosphere.

## SCIENTIFIC GOALS OF M-DLS EXPERIMENT

In more than 40-year history of Martian spacecraft exploration, primary scientific goals of the stationary landing platforms were mainly reduced to providing so called “ground truth”, i.e. *in situ* information necessary to validate and calibrate remote sensing data received by the orbiters. Besides this traditional niche, M-DLS experiment implies broader context due to its ultra-high spectral resolution. In general, M-DLS scientific objectives include three major blocks. The first one is concerned with modern climate and meteorology, and implies monitoring of water vapor and HDO, carbon monoxide, and winds. Second block is related to Mars evolution and implies precision measurements of isotopic ratios in volatiles, including water, carbon monoxide, and carbon dioxide. Finally, M-DLS experiment is expected to advance in the methane problem, which remains to date a major challenge in Mars studies.

Modern Martian climate is characterized by the thermal regime, atmospheric general circulation, and global cycles of carbon dioxide, water, and dust, with all those components being deeply interconnected. We leave dust cycle beyond M-DLS topics, as aerosol phase cannot be observed by means of laser and heterodyne spectroscopy. Atmospheric temperatures are also hard to retrieve from high resolution spectroscopy in the NIR and MIR spectral ranges. However, direct Doppler measurements of wind will be the first such

## THE INSTRUMENT

M-DLS combines inside a single frame two self-consistent instruments - a classical laser spectrometer and infrared heterodyne spectro-radiometer. The two parts share key subsystems, such as electronics, laser assembly, fiber-optical tract and the reference gas cell. Some subsystems are specific for each method, such as air sampling system for *in situ* measurements and suntracking system for heterodyne observations. A schematic of the instrument’s optical design is presented in Figure 1(a). From the point of view of spectral range, it consists of two channels: near-IR, marked by black color, and med-IR marked by blue. Thin curves on the sketch mean single mode optical fibers which serve as a universal radiation carrier in the instrument.

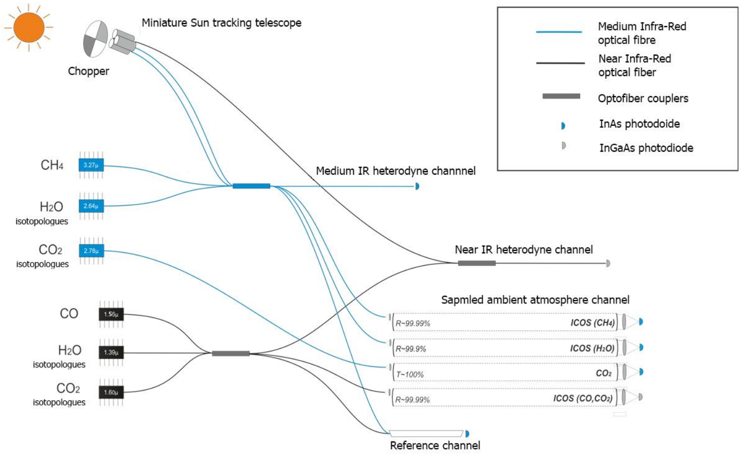

Figure 1. M-DLS optical scheme. NIR part is marked by black, MIR (3-μm range) part – by blue color. Thin curves are single mode optical fibers, thin horizontal bars – single mode couplers. Wired thick bars are tunable diode lasers with distributed feedback, targeting specific rotational lines of their respective molecules. On the left upper corner there is a solar microtelescope with sun tracking system, on the right lower corner – gas cell assembly, including single pass reference cell and a set of analytical cells designed for specific spectral ranges. Each laser is tuned to one or several specific spectral features characterizing target molecules.

Each channel includes a laser set, single mode optical fibers and couplers, and analytical gas cells. Solar microtelescope with the Sun tracking system and reference cell serving for stabilization of laser radiation are shared by both MIR and NIR channels. Lasers are located in the electronic block, occupying a rear side of the instrument, attached to the spacecraft frame. Composite multipass optical cell and the reference cell are located inside the main instrument's box along with the aspiration system, which includes low-pressure pump and a set of pipes, valves and filters. Another part of the air sampling system, telescopic snorkel, is placed at the instrument's upper panel along with the sun tracking scanner. All optical elements are wired with each other by a bundle of single mode optical fibers and directional couplers. A special technology of non-quartz fiber welding for manufacturing single mode fiber couplers in the MIR spectral range is being developed. General M-DLS layout is presented in Figure 2.

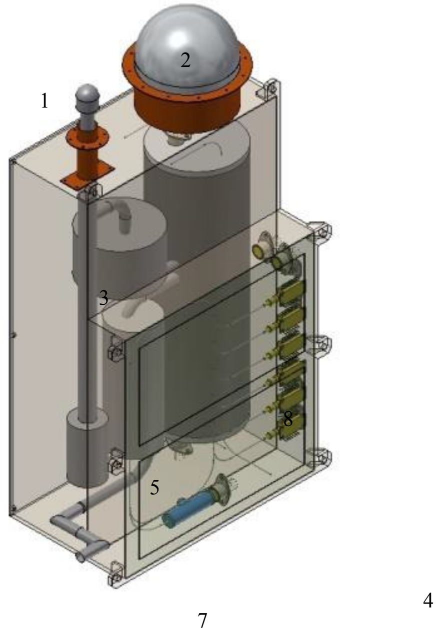

Figure 2. Preliminary M-DLS layout. Smaller container with laser set and electronics is attached to the spacecraft frame through the front panel. Larger container with gas sampling system and analytical cell assembly carries a snorkel (left) and solar microtelescope (right) on the upper panel. 1 – snorkel (air inlet), 2 – Sun tracking scanner, 3 – air filter, 4 – analytic gas cell, 5 – air pump, 6 – air outlet, 7 – reference gas cell, 8 – laser set.

Both NIR and MIR channels implements the principles of laser and heterodyne spectroscopy. A tunable diode laser fed by variable pump current generates radiation with the frequency sweeping over spectral range of interest. According to the adopted algorithm, laser frequency is ramping according to a saw-like law, with amplitude about 1 $cm^{-1}$ and period of 10 ms. A portion of laser radiation is redirected into the reference cell filled by a mixture of gases that provides absorption near spectral features to be studied. The signal from the reference channel is analyzed by the instrument's data processing unit and fed back to laser controller in order to provide stability of frequency sweeping within 1-2 MHz. Another portion of radiation is put into the analytical multiple pass cell. As laser radiation frequency is swept, it reveals selective absorption by gas sample pumped into the cell from the ambient atmosphere. In order to achieve ultimate sensitivity in minor component detection, including methane, we plan to employ an analytical cell based on the principle of integrated cavity output spectroscopy (ICOS)[5]. The method implies very high reflectivity of the cell windows, up to $R = 0.9999$, with entrance beam being slightly of-axis to avoid resonant fringes. Our preliminary experiments show that an effective optical path of ~1.5 km could be readily achieved. Laboratory measurements confirmed that special attention should be paid to cleansing air samples from suspended dust and other aerosol components. For this purpose, M-DLS air sampling system includes a cascade of filters based on fine inorganic fibers. Atmospheric samples are moved in and out the instrument by a system of two valves and ventilatory pump. After evacuation of the analytic gas cell, air is sucked inside through the filter by atmospheric pressure, isolated from the atmosphere and analyzed by laser spectrometer until next evacuation. A typical daily cycle of measurements implies treatment of 4 samples per sol.

Spectroscopic measurements in the heterodyne mode are planned during the daytime by direct Sun observations. Solar beam from the tracking scanner modulated by a chopper is captured by an assembly of gradient lenses, which redirect it into several single mode optical fibers, operating in both NIR and MIR spectral ranges. In order to save MIR lasers power, independent heterodyne channels for each molecule are designed in this spectral range, with separate interface to the Sun tracking scanner. The topology of NIR heterodyne channel assumes a single fiber for solar interface sequentially coupled to all lasers. The cycle of heterodyne measurements includes capture and tracking of the Sun with simultaneous collecting data within ~15 min. Averaged heterodyne spectra are transferred to the Earth along with *in situ* data measured in the analytic gas cell.

## EXPECTED RESULTS

Scientific results expected from the instrument include those related to *in situ* and remote measurements. Studies of the local atmosphere include precision concentration measurements of H2O, CO, CO2 and their isotopes, and CH4. Sensitivity to each species is determined by spectral line strength, effective optical path, and noise in the system. Expected quantities are summarized in Table 1. We expect that the accuracy of methane detection will overcome the results of SAM instrument onboard Curiosity rover[6] due to the larger effective path in the ICOS analytical cell. Similar accuracy is expected in the heterodyne channel, where the path, equivalent to one scale height, is ~6 times as large as in the cell, but the system noise is stronger.

Table 1. Sensitivity and accuracy of M-DLS *in situ* measurements.

| Molecule | Wavenumber, $cm^{-1}$ | Concentration | Accuracy | Precision |
|---|---|---|---|---|
| $H_2O$ | 3764,59913 | ~200 ppm | <40 ppb | <0.1% |
| $H_2{}^{18}O$ | 3765,09081 |  | <0.8 ppb | <0,2% |
| HDO | 3764,87629 |  | <0.7 ppb | <0,2% |
| $CO_2$ | 3580,786 | ~95% |  | ~0,1% |
| $^{13}CO_2$ | 3580,843 |  |  | ~0,1% |
| $CO^{18}O$ | 3580,907 |  |  | ~0,1% |
| $CO^{17}O$ | 3580,970 |  |  | ~0,1% |
| CO | 6385,8 | ~600 ppm |  | ~0,1% |
| $CH_4$ | 3057,68728 | <1 ppb | 50 ppt |  |

The most intriguing capability of the heterodyne channel consists of vertical profiling of measured quantities – abundance of particular species and wind velocity projection. Unlike the Earth atmosphere where pressure broadening dominates, on Mars spectral lines are mostly Doppler broadened. Hence, the link of each part of spectral line profile to a particular altitude range is not evident. However, with a priori known thermal profile, e.g. predicted by a GCM or measured simultaneously from the ExoMars orbiter, vertical profiles of atmospheric species and wind may be retrieved. In order to assess capabilities of the instrument, a numerical experiment has been carried out. Atmospheric state predicted by the Mars Climate Database[7] was used to generate high resolution synthetic spectra. Then random perturbations corresponding to the expected noise lever was superimposed, and data inversion procedure was applied. An example of such an inversion related to water vapor vertical profile is shown in Figure 3. It is evident that, providing sufficient signal-to-noise ratio, water vapor profile can be measured with unprecedented accuracy, including key near-surface altitude range, not accessible by solar occultation techniques. Similarly, numerical experiments predict that the profile of the line-of-sight wind projection can be determined below 30 km.

Thus M-DLS is a powerful and promising instrument, which is expected to address key questions on the chemistry, climate and meteorology of the Red planet. A combination of *in situ* and remote sensing analyses, along with the implication of novel photonic technologies, provide its unique sensitivity and profiling capabilities, while retaining modest parameters in dimension, power, and weight.

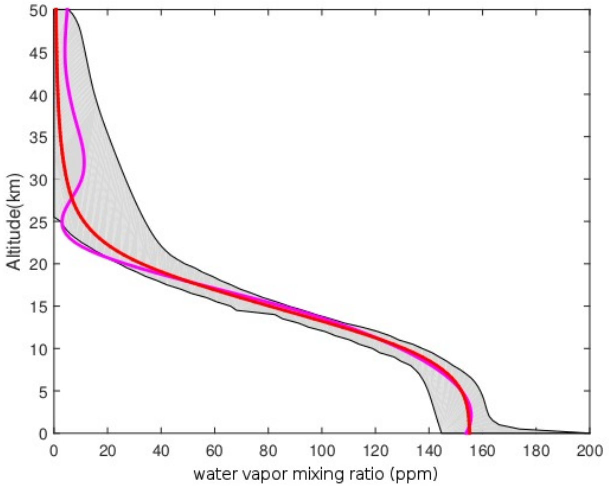

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Figure 3. An example of numerical experiment checking M-DLS' heterodyne channel performance in water vapor profiling. Pink curve – "true" profile borrowed from the EMCD[7]. Red curve –profile retrieved from the randomy perturbed synthetic spectrum. Grey area shows confidence intervals of retrievals.

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