A MARS-ORBITING 2-MICRON LIDAR SYSTEM TO MONITOR THE DENSITY, WINDS AND DUST OF THE ATMOSPHERE OF MARS

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Abstract:

Future robotic missions to Mars and, eventually, human missions to Mars will require landing massive spacecraft with "pin point" accuracy, e.g., the planned Mars Sample Return (MSR) mission will require "pin point" landing accuracy to rendezvous with the previously cached Mars samples to be returned to Earth and the first human mission to Mars, with payloads estimated to be in excess of 40 metric tons, must land very close to the cargo spacecraft that precede it on the journey to Mars. Hence, "pin point" entry, descent and landing (EDL) has become a major technological driver in future massive robotic and human mission to Mars [1]. To achieve "pin point" EDL on Mars, we must predict the atmospheric density, atmospheric winds and atmospheric dust level to an accuracy previously unobtainable. To develop an accurate and precise predictive model of the atmosphere of Mars, we propose a Mars-orbiting LIDAR system to measure/monitor the density, winds and dust in the atmosphere of Mars over two Mars years. The LIDAR measurements will be used to develop an accurate model of the atmosphere of Mars to be used for "pin point" EDL for future Mars missions.

Introduction:

Planetary winds have implications to understanding planetary weather and conducting planetary exploration. In the case of Mars, the interplay between winds, dust storms and the radiative feedback is critical to the prediction of operational meteorology but remains poorly understood. Two major components of the Martian weather are the episodically strong winds and the dust storms. Both have implications to understanding Martian weather and to the prediction of hazardous conditions for landing and exploration on the surface of Mars. The feedback between winds (driven by thermal gradients), dust storms (sustained suspension of high optical depth dust clouds) and the consequential changes in the thermal gradients, is recognized as fundamental to the Martian weather. In addition to the weather/climate issues, the knowledge of the 3-dimensional wind field would be beneficial and could be critical to both the design and execution of future robotic and human expedition missions. As an example, the wind field (and wind shear throughout the atmosphere) is a crucial factor in the entry, descent, and landing of instrumented craft and subsequent airborne and surface exploration.

Approach:

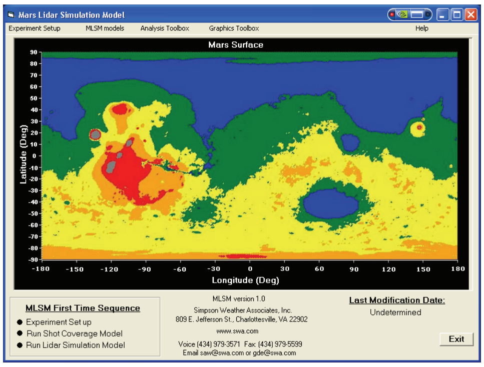
The lack of measurements of Martian atmospheric density in the 30-80 km range, dust storm formation and movements, and horizontal wind patterns in the 0-20 km range pose significant risks to aerocapture, and entry, descent, and landing (EDL) of future robotic and human Mars missions. Systematic measurement of the Mars atmospheric density and winds will be required over several Mars years, supplemented with day-of-entry operational measurements. To date, there have been 6 successful U.S. robotic landings on Mars (the two Viking landers, Mars Pathfinder, MER: Spirit and Opportunity, and Mars Phoenix). Atmospheric density and wind reconstruction has been performed for each of these entries. At present, all of NASA's Mars atmospheric density and wind models have these 6 entries (at widely scattered positions and seasons) as their basis, supplemented by coarse orbital measurements of atmospheric opacity and temperature. This lack of data leads to a large uncertainty in prediction of the Martian atmospheric density and winds in the altitude regime where deceleration of landers will occur. This uncertainty will have a dramatically large impact on mass, cost and risk. The proposed 2-μm Doppler/DIAL lidar system will provide the critically needed density and winds data to reduce the risks of future Mars landing missions.

Research programs were initiated at NASA Langley Research Center during 2005, jointly funded by NASA Science Mission Directorate and Exploration Systems Mission Directorate, to first model the lidar's performance and then build a breadboard lidar system demonstrating a measurement capability for wind, CO_2 concentration, and aerosols suited to meteorological and climatological application for Mars. This 2-μm coherent DIAL system can simultaneously measure wind by a Doppler technique and CO_2 concentration by a differential absorption technique. Since the source of the backscatter is atmospheric aerosols, aerosol/dust profiling is inherently included.

The first step in development was to model performance of the lidar in the Martian atmosphere. Simpson Weather Associates (SWA) and NASA/LaRC conducted a study to compare several lidar concepts that could provide critical observations of winds, aerosols and, perhaps, gases from orbit around Mars. During the two year study we defined the target atmosphere and observational requirements with explicit reference to lidar technologies; modified an existing Doppler Lidar Simulation Model for application to Mars missions; generated the lidar system performance requirements; and identified the technology "tall poles" such as power demands, weight and space hardening. During this study, the issue of atmospheric density and its role in managing entry, descent and landing became a pursuit to model the application of 2-µm coherent DIAL to providing density profiles during the entry phase. In this presentation we review briefly the approach and findings of this study.

Mars Lidar Simulation Model (MLSM):

Prior to establishing lidar technology requirements for a Mars mission, an existing Doppler wind Lidar Simulation Model (DLSM) was modified to work with Mars atmospheres (Figure 1).



MLSM First Time Sequence
- ● Experiment Set up
- ● Run Shot Coverage Model
- ● Run Lidar Simulation Model

MLSM version 1.0
Simpson Weather Associates, Inc.
809 E. Jefferson St., Charlottesville, VA 22902
www.swa.com
Voice (434) 979-3571 Fax: (434) 979-5599
Email saw@swa.com or gde@swa.com

Last Modification Date:
Undetermined

Figure 1: The main page for the Mars Lidar Simulation Model based upon the established Doppler wind Lidar Simulation Model used in many space based instrument studies.

Given that the initial choice of lidar receiver/detection technology was 2-µm coherent, the aerosol backscatter and CO_2 radiative properties at that wavelength had to be specified. Data from the TES and climate data sets from the European Mars GCM (Forget - LMD; Lewis - AOPP (Oxford)) were used to generate reference profiles for use in the MLSM (Mars Lidar Simulation Model). The reference wind profile used to bound the study in terms of wind speeds and vertical distribution of winds is shown in Figure 2. In terms of aerosol backscatter, we made the following assumptions:

- work to column optical depths at 9-µm
- Use published size distributions and inferred dust physical properties to convert to 2-µm properties
- Assume constant mixing ratio 0-40 km.
- Assume constant mixing ratio for CO_2

The MLSM optical properties code was run for several size distribution parameters until observed optical depths were computed. Once the backscatter coefficients and vertical profiles were established, several weather situations were chosen from the Mars GCM (LMD) which provided 3D fields of temperature, pressure and density during various dust load scenarios.

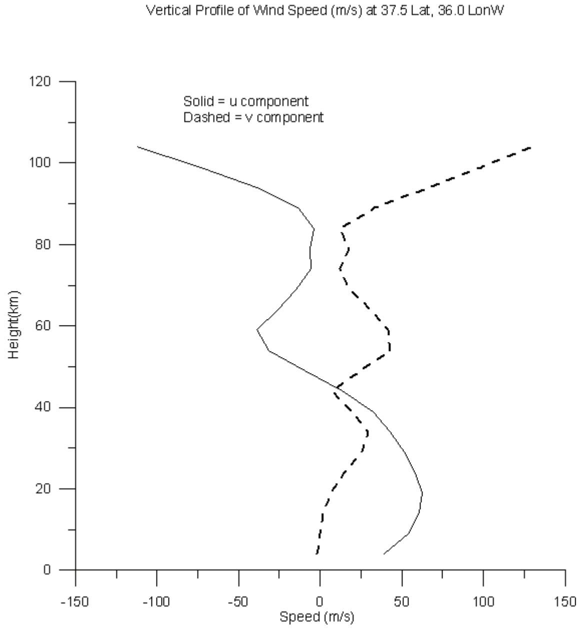


Figure 2: Reference wind profile

A critical feature calculated by the MLSM for predicting lidar performance is the dust backscatter throughout the atmosphere. Qualitatively, the backscatter is expected to be quite large—Mars is known to be a rather dusty place—compared to the calculations lidar researchers are accustomed to in designing for the Earth atmosphere. An interesting note is in the nomenclature of studying Mars and Earth: on Earth the term used for backscattering particles is "aerosol," whereas for Mars the term is "dust." An example calculation of the backscatter coefficient for Mars (and Earth for comparison) is shown in Fig. 3.

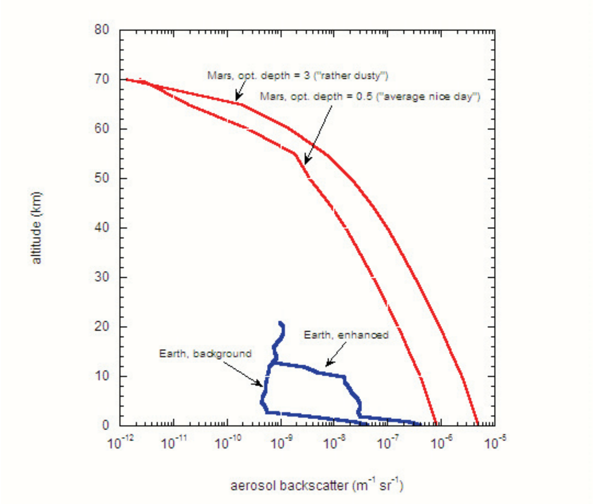


Figure 3: Atmospheric dust backscatter on Mars (red curves) and Earth (blue curves).

This calculation demonstrates the very high level of backscatter that would be encountered in Mars—several orders of magnitude greater than found on Earth. Such a high level of backscatter is good for lidar operation in that very strong signal levels can be encountered with a modest lidar design.

Another aspect of the Martian atmosphere illuminated by this modeling effort is the effect of the low atmospheric pressure of Mars on the shape of the CO_2 absorption lines. The absorption lines, which are the basis for the DIAL measurements, are rather strong and narrow compared to the case for Earth—Figure 4 quantifies this comparison. Control of the laser spectrum becomes critical for the Mars application.

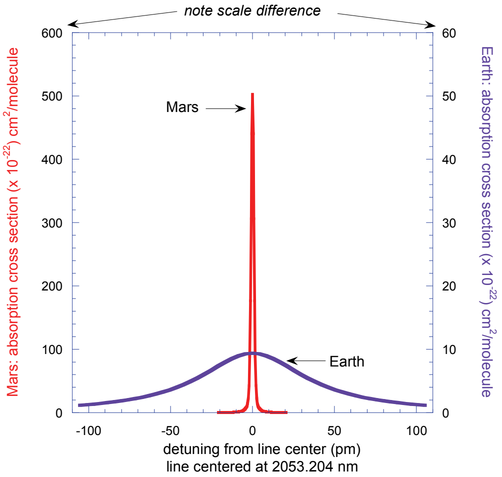


Figure 4: Absorption line parameters matching the laser wavelength of Ho:Tm:LuLiF at ground level for both Earth and Mars.

With the MLSM loaded with parameters of the Mars atmosphere analysis could proceed of how well the lidar would be able to measure wind. Figure 5 shows the results of this analysis for two cases: a "clear" day and a "dusty" day. These two cases represent two seasonal extremes in the course of a Martian year. The "dusty" case does not, however, represent the occurrence of dust storms that occasionally occur on Mars. The lidar design used in this case was of 250-mJ pulse energy, 10-Hz repetition rate, 2053-nm wavelength, 0.5-m telescope aperture, and a satellite orbit of 400-km altitude. As will be described in a following section, such a lidar design is quite feasible.

This simulation shows that wind measurements can be readily made in the altitude region of 0-20 km where the primary interest lays. Measurements extended to higher altitudes are also quite likely, benefiting a more complete climatological characterization of the atmosphere.

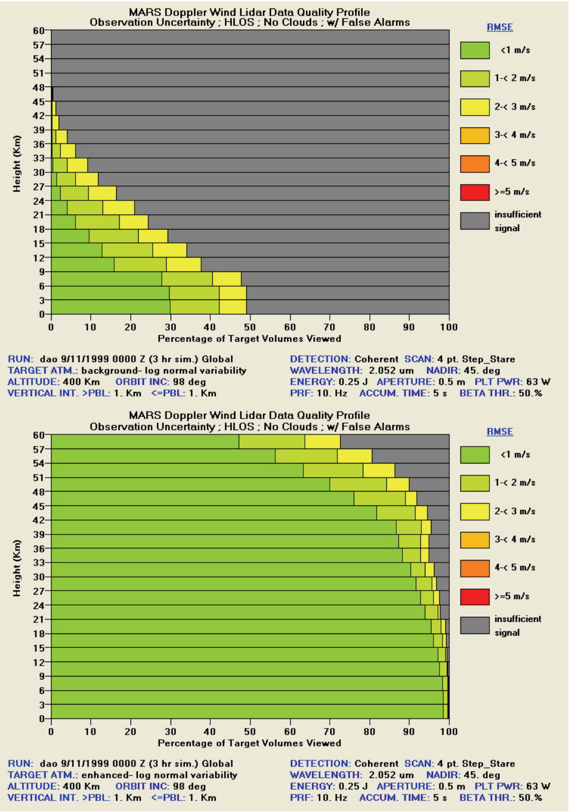


Figure 5: MLSM analysis of wind measurement performance for two cases of atmospheric conditions: a "clear" day (top plot) and "dusty" day (bottom plot).

With regards to making measurements of the atmospheric density, we investigated the potential performance of a 2-µm coherent wind lidar operated in the double pulse mode. By having the two pulses at different frequencies, a DIAL mode could be used to detect CO_2 in the atmosphere. Although the absolute concentration of CO_2 would be hard to measure accurately, SWA developed an approach that could detect variations of the atmospheric density from a standard atmosphere. Using the CO_2 attenuation profiles (figure 6) derived from the MARS GCM, we were able to show that density variations of < 1% could be detected along the entry and descent path.

Baseline Lidar System Design:

The wind performance simulation of Figure 5 was run with lidar parameters believed to be feasible from many years of previous research on 2-µm lasers and lidar system design [2-4]. Specifically these parameters include 250-mJ pulse energy, 10-Hz pulse repetition rate, 150-ns pulsewidth, and 0.5-m telescope diameter. For CO_2 DIAL measurements two target absorption lines are possible at 2053.204-nm and 2050.967-nm, corresponding to possible laser materials of Ho:Tm:LuLiF or Ho:Tm:YLiF, respectively. Either on-line wavelength would work for DIAL; the choice of line can be left to other considerations of the laser design. Wind measurements are made at a wavelength well away from line center

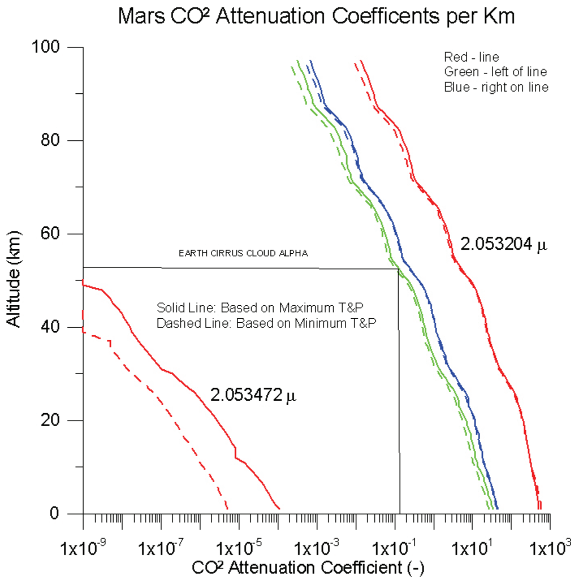


Figure 6: Derived vertical profile of the differential extinction for the two wavelengths produced during the DIAL mode of operations for the 2-µm laser (as distinguished from the Doppler wind mode).

and a wide range of suitable off-line wavelengths are available for either laser crystal selection.

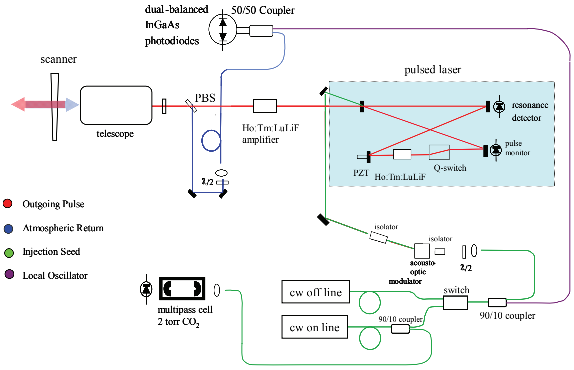


Figure 7: Layout of the 2-µm coherent wind/CO_2 and aerosol/dust profiling lidar.

Figure 7 illustrates the architecture of the lidar; a design similar to that used in previously demonstrated lidars for wind and CO_2 measurements. The heart of the lidar is the holmium laser crystal pumped from the side by diode laser arrays and enclosed in a ring resonator. This pulsed oscillator is capable of producing in excess of 100-mJ per pulse, but its output can be de-rated to preserve the diode pump laser lifetime. An external amplifier, also a side-pumped holmium crystal, provides gain to reach the 250-mJ level [5]. Spectral purity and wavelength tuning are achieved by the injection seeding technique, also a well-established technique from prior work. Two wavelength settings are used as set by continuous-wave lasers—one wavelength is tuned to the absorption line and the other laser is tuned off of the absorption line. For wind measurements, only the off-line wavelength is used. For DIAL measurements the wavelengths are alternated as the pulsed laser is fired in a double-pulsed format. Double-pulsing involves firing the laser twice during a pumping cycle; these doublets then repeat at a 10-Hz repetition rate. Double pulsing is a key feature in the DIAL measurement in that the spacing between pulses of the doublet (on the order of 100-ms) is short enough that the atmosphere does not change between the on-line and off-line measurements. The pulsed laser output is transmitted to the atmosphere via an off-axis telescope. After expansion by the telescope, the lidar beam can be scanned to facilitate wind measurements or off-nadir CO_2 measurements if desired.

Conclusions:

Development of the Mars Lidar Simulation Model and an assessment of technology have shown that profiling wind and aerosols from an orbiting satellite would provide much useful science data. The lidar parameters needed are relatively modest and designs already underway for Earth measurement applications would also meet the requirements for Mars. Performance of the DIAL for measuring CO2 concentration, and thus atmospheric density, is still not quantified. This is very preliminary work with additional lidar technology issues yet to be addressed. These issues include platform power and thermal management requirements.

References:

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