PERFORMANCE ESTIMATES OF THE PHOENIX MARS SCOUT LIDAR SYSTEM

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ABSTRACT

The Phoenix Mars Mission, the first of NASA's "Scout Program," is scheduled to launch in August of 2007, arriving at the Martian surface 10 months later. The Lander will be equipped with a lidar, operating at both visible (532 nm) and infrared (1064 nm) wavelengths, and will be employed to measure profiles of Martian scatterers, such as ice and dust.

For the purposes of mission planning, the expected lidar return signals for the photon counting 532 nm channel have been modeled, and some initial results are presented.

1. INTRODUCTION

The Dalhousie Lidar Performance Model (DLPM) employs estimates of particle scattering calculations, instrument specifications, and ambient skylight calculations, into the lidar equation:

$$P(z) = N_0 \cdot C \cdot \eta \cdot O(z)\left(A/z^2\right)\left(c/2\right)\beta(z) \times \exp - 2\left(\int_0^z \alpha(z) dz\right) + P_{sky} \qquad (1)$$

to estimate the return signals of the Phoenix Lidar. $P(z)$ is the rate of detected photons, N_0 is the number of photons emitted by the laser per pulse, η is the specified total system efficiency, $O(z)$ is the telescope overlap function, c is the speed of light, z is the altitude, A is the area of the telescope, $\beta(z)$ is the total volume backscatter cross-section, $\alpha(z)$ is the total extinction coefficient, P_{sky} is the detection rate of photons from sky light. The parameter C is defined as the "instrument efficiency factor" and accounts for unknown losses of signal within the system.

1.1 Estimation of atmospheric terms: $\alpha(\lambda, z)$ and $\beta(\lambda, z)$

The scattering coefficients for the molecular atmosphere (~95% CO_2, assumed here to be 100%), were calculated from estimates of the Number Density ($N_{Atmos.}$), and scattering cross sectional area (σ) or volume scattering cross sectional area (σ^π):

$$\alpha(z)_{Atmos.} = N_{Atmos.}(z) \cdot \sigma_{CO_2} \text{ and} \qquad (2)$$

$$\beta(z)_{Atmos.} = N_{Atmos.}(z) \cdot \sigma^{\pi}_{CO_2} \,. \qquad (3)$$

Estimates of σ and σ^π were obtained from the CO_2 values given in Measures [1], while estimates of $N_{Atmos.}$ were made by modeling the atmosphere using an exponentially decreasing function with a scale height of 11 km; a surface pressure of 7 mb; and a surface temperature of 240 K.

Dust parameter estimates required a much more extensive calculation routine. The dust particle size distributions and number densities were provided from the Martian dust modeling work of Taylor *et al.* [3] as fitted parameters of the gamma distribution, $a(z)$, $b(z)$ and $c(z)$, given:

$$n(R,z) = c(z) \cdot R^{(1-3b(z))/b(z)} \exp\left(\frac{-R}{a(z)b(z)}\right) \qquad (4)$$

Here R is the particle radius and $n(R, z)$ is the instantaneous number density at R. Values of $\sigma_{Dust}(z)$ and $\sigma^{\pi}_{Dust}(z)$, i.e. ensemble averaged values over the dust distribution, were calculated by employing estimates of $a(z)$, $b(z)$ and the dust refractive indices inferred from [4], into the Mie code of [2]. The total number densities, $N_{Dust}(z)$, were determined by numerical integration of Eq. 4 over all R. The volume scattering cross-sections and extinction coefficients for Martian dust were thus calculated using:

$$\alpha(z)_{Dust} = N_{Dust}(z)\cdot\sigma_{Dust}(z) \text{ and} \quad (5)$$

$$\beta(z)_{Dust} = N_{Dust}(z)\cdot\sigma^{\pi}_{Dust}(z)\,. \quad (6)$$

The total extinction coefficients, $\alpha(z)$, and volume backscatter cross-sections, $\beta(z)$, for the Martian atmosphere were calculated as the sum of molecular and dust terms.

The Lidar ratio, defined as $\alpha(z)$ / $\beta(z)$, was subsequently calculated for one Martian day (sol), and the results are given in Fig. 1.

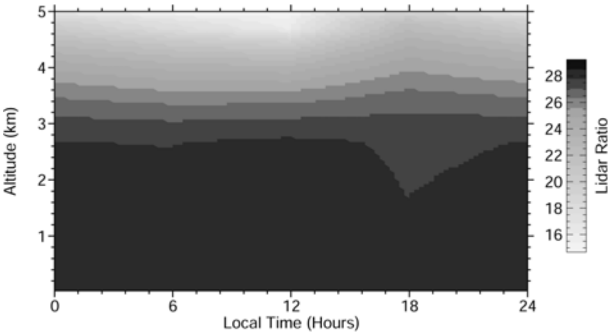

Figure 1. Lidar Ratio as a function of local time and altitude.

The calculated lidar ratios of Figure 1 illustrate the variation in dust distributions as a function of altitude and time of day. These variations are due to the interplay between gravitational settling and dust uplifting, as estimated in [3].

1.2 Estimation of Instrument Terms: N_0, η, $O(z)$ and A

The Phoenix Lidar will consist of a transmitter operating at 100 Hz and 0.5 mJ at 532 nm, while the receiver consists of a 10 cm Cassegrain telescope with a 1.5mrad Field-of-View. Values for the transmitter photon number, total efficiency (including transmitter, receiver and the detector efficiencies) and receiver Aperture (N_0, η, and A, respectively) were determined from the specifications provided by the system's manufacturers (Optech and MacDonald Dettwiler & Associates Ltd.).

The overlap function, $O(z)$, for this biaxial system was estimated by employing basic lens theory and the manufacturers specifications. It is estimated that overlap of 5%, 50% and 95% will occur at heights of 84 m, 146 m and 232 m, respectively.

1.3 Estimation of the Efficiency Factor: *C*

Although signal loss owing to the efficiency of optical or electronic components can be estimated using the manufacturer's specifications (η), in practice, it is not possible to account for all sources of loss. To compensate an instrument efficiency factor, *C*, was required. An estimate of *C* was determined by performing a calibration experiment using terrestrially based lidar systems of similar design as follows: The molecular scattering signals for clear air were compared with predicted values from a radiosonde density profile and a Rayleigh scattering model. The unknown efficiency factor is thus the multiplicative offset between the observed and modeled signals profiles, which, for this study, was estimated to be 0.001.

1.4 Estimation of Ambient Skylight: P_{sky}

Modeling results for the ambient skylight (i.e. spectral radiance, $S_B(\tau, SZA)$) on Mars, under different dust loading (given by total optical depth (τ)), and at different Solar Zenith Angles (*SZA*), was provided by [5]. The estimated contribution to the Lidar signal is given as:

$$P_{sky} = \frac{S_b(\tau, SZA)\Omega_0\Delta\lambda\cdot A\eta}{hc/\lambda} \quad (7)$$

where Ω_0 is the telescope solid acceptance angle; $\Delta\lambda$ is the optical bandwidth at 532nm; and h is Plank's constant. Values of τ were determined from integration of the extinction coefficients, $\alpha(z)$, over all z; while values of *SZA* were estimated from simplified calculations of Mars' orbit.

1.5 Signal to Noise Ratio

Artificial Poisson Noise was also simulated for each profile. The Signal to Noise Ratio (SNR) for a single profile was calculated using:

$$SNR = \sqrt{P(z)\cdot\Delta t'}\,, \quad (8)$$

given the temporal (height) resolution:

$$\Delta t' = \frac{2\Delta z'}{c} \quad (9)$$

For the Phoenix lidar, the default temporal (height) resolution was chosen to be 333 ns (50 m). There will also be an enhancement of the Signal to Noise Ratio upon integration (SNR_{Int}) of consecutive profiles following:

$$SNR_{Int} = SNR \cdot \sqrt{\#\ Integrated\ Profiles} \quad (10)$$

2. CALCULATED LIDAR RETURN SIGNALS

The lidar return signals were thus calculated over an entire sol (given here as 24 hours of Martian time) in 15 minute increments, or scans. The average Signal is given in Fig. 2, which illustrates that the scattered laser light owing to molecular scattering is approximately two orders of magnitude smaller than for scattering due to Martian dust.

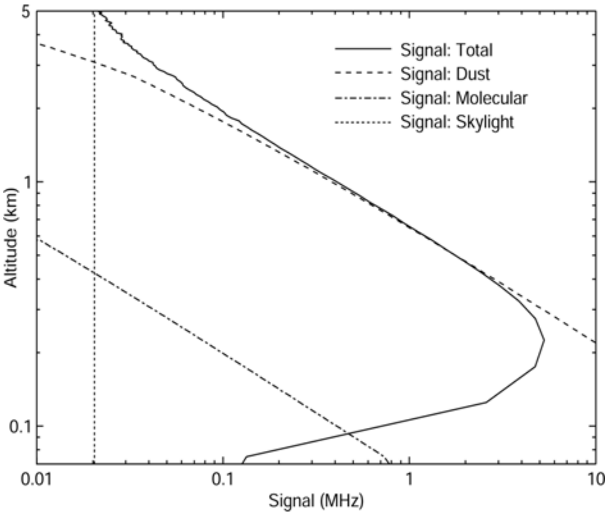

Figure 2. Calculated Lidar Return Signal, Averaged over a single Martian sol.

The contour plot of Fig. 3 depicts individual 15 min Lidar return profiles over an entire sol, corrected for background signal and range dependence (z^2). An increase in low altitude signal from 9-18 hours is due to an increase in dust uplifting over this period.

Return signals recorded by a Martian based system will depend upon both the dust loading, and the dust size distribution. Unlike terrestrial systems which typically exhibit a total signal which varies little with time, constantly changing dust conditions may cause signals recorded by the Phoenix Lidar to be extremely variable. As an example, Fig. 4 illustrates how the Signal to Noise Ratio (SNR) is affected by artificially altering the total dust loading conditions, while maintaining the same dust size distribution.

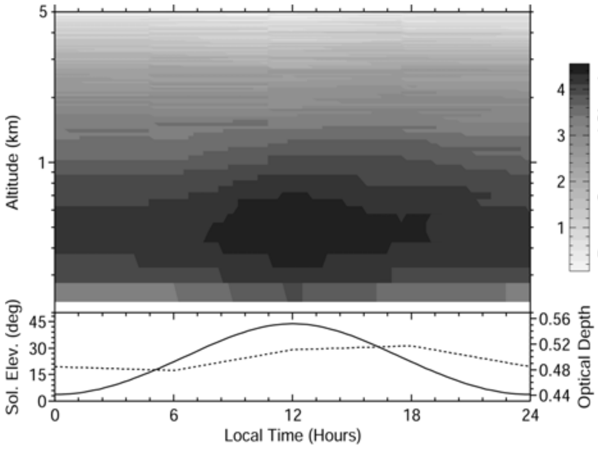

Figure 3. Contour plot of Calculated Lidar Return Signals for a single sol in 15 minute increments (Background subtracted and Range Corrected; given in units of 10^5MHz·m^2). The Solar Elevation (solid line) and total optical depth at 532 nm (dotted line) are also provided for comparison.

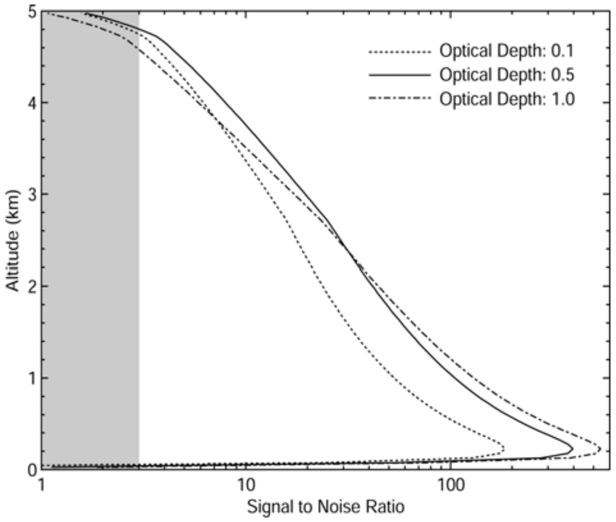

Figure 4. Calculated Signal to Noise Ratio, Averaged over a single Martian sol. The dust size distribution for each profile was kept identical, while the total dust Number Density was artificially adjusted to obtain the desired optical depth. The shaded area indicates SNR < 3, where detection of features may not be possible. Optical depths were calculated at 532 nm.

It is also interesting to note that for the Phoenix Lidar there are optimal Martian dust loading conditions for obtaining signals at various heights. Examination of Fig. 4 portrays how laser attenuation will reduce the maximum observable height for the high dust loading case (optical depth = 1.0); while for the low dust loading case (optical depth = 0.1), the SNR is generally reduced, owing to the low number of scatterers in the atmosphere. The median case (optical depth = 0.5), appears to give the best overall performance, which is serendipitously the predicted optical depth [6] at the Phoenix landing site during the planned operational period.

Additional data, such as lidar profiles collected at 1064 nm, and total optical depths measured at several wavelengths using the Phoenix Stereoscopic Imaging Camera, will likely also be used to aid in the analysis of Martian dust.

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