The case for a multi-channel polarization sensitive LIDAR for investigation of insolation-driven ices and atmospheres

Planetary Science Decadal Survey White Paper

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"There once was a LIDAR with Polarized Holes,
Made to observe Mars' Mysterious Poles,
It measured Volatiles and Ices ...
and used Multispectral Devices ...
And met many of our Mars Climate Goals."

- Anon, 2020

Key point of this white paper: All LIDAR instruments are not the same, and advancement of LIDAR technology requires an ongoing interest and demand from the community to foster further development of the required components. The purpose of this white paper is to make the decadal survey panel aware of the need for further technical development, and the potential payoff of investing experimental time, money and thought into the next generation of LIDARs.
Technologies for development: We advocate for future development of LIDAR technologies to measure the **polarization** state of the reflected light at **selected multiple wavelengths,** chosen according to the species of interest (e.g., H_2O and CO_2 in the Martian setting).
Key scientific questions: In the coming decade, dollars spent on these LIDAR technologies will go towards addressing key climate questions on Mars and other rocky bodies, particularly those with seasonally changing (i.e. insolation driven) plumes of multiple icy volatiles such as Mars, Enceladus, Triton, or Pluto, and insolation-driven dust lifting, such as cometary bodies and the Moon. We will show from examining past Martian and terrestrial lidars that orbital and landed LIDARs can be effective for producing new insights into insolation-driven processes in current planetary climate on several bodies, beyond that available to our current fleet of largely passive instruments on planetary missions.

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1. Preamble and Science Themes

This white paper is intended to make the decadal survey panel aware of the type and amount of information about the present day Martian climate that would be acquired by a multiple-wavelength, active, near-infrared (NIR) LIDAR instrument. This instrument would measure the reflected intensity and polarization characteristics of backscattered radiation from the surface via the atmosphere, such as that described by Brown et al. [1]. Science output from this type of dataset would address the following three major science themes:
Science Theme 1. Surface Global, night and day mapping of H_2O and CO_2 surface ice,
Science Theme 2. Ice Clouds: Unambiguous discrimination and seasonal mapping of CO_2 and H_2O ice clouds
Science Theme 3. Dust Aerosols: Inference of dust grain shapes and size distributions from multiwavelength polarization measurements.
Knowledge generated from such an instrument has the potential to fundamentally shift our understanding of modern-day Martian volatile transport and deposition. As a bonus, this lidar would permit a continuation of the MOLA geodetic mapping of Mars to a point where a global network suitable for registration of high resolution images (e.g. HiRISE).

2. Martian Example Case Study LIDAR - *ASPEN*

Our present understanding of the sublimation of surface H_2O and CO_2 ices and related atmospheric changes on Mars is the result of recent polewide and seasonal studies of springtime recession using the Mars Climate Sounder [2], CRISM [3], and MARCI [4] instruments on MRO, the OMEGA instrument on Mars Express [5-6], the THEMIS instrument on 2001 Mars Odyssey [7] and the TES instrument on Mars Global Surveyor [8]. These investigations have steadily advanced our understanding of major polar processes. However, the observations of the spatially localized springtime recession phenomena, such as geysers (gas/dust jets, which are inferred, and have not been directly observed) [9], and observations of the asymmetric retraction of the seasonal cap [6,10] lead us to ask a key scientific question – what role does spatially localized and temporally intermittent deposition of ices and dust during fall and winter [10] play in the annual CO_2 and H_2O cycles that are instrumental the climate of modern-day Mars? In the remainder of this white paper, we discuss an instrument optimized for Martian conditions called "*Atmospheric/Surface Polarization Experiment at Nighttime" (ASPEN)* [1], designed to directly address the role of ice and dust deposition in Martian climate.

Instrument Specs. ASPEN would be a multi-wavelength, altitude-resolved, active, near-infrared (NIR: covering 1.52-1.59 μm) instrument to measure the reflected intensity and polarization of backscattered radiation from planetary surfaces and atmospheres. The currently envisioned spacecraft instrument utilizes multiple diode lasers, each operable at a different wavelength, amplified by a fiber laser stage (commonly referred to as a master-oscillator power-amplifier or MOPA). The laser would operate in a high repetition (10 kHz) low pulse energy (40μJ) configuration. The receiver side will consist of a telescope coupled to an indium gallium arsenide (InGaAs) high dynamic range avalanche photo detector (APD).

Martian Operations. As currently envisioned, the ASPEN instrument would operate as a line profile instrument, in a similar manner to the MOLA lidar. The instrument is best suited for an MGS or MRO-type 250–320 km elliptical/circular orbit but could also operate in an elliptical orbit with reduced sensitivity during apoapsis. For optimized polar measurements, orbital inclination should be between 85° and 92.8°. An elliptical orbit such as that mentioned in the recent MSO SAG document would allow lidar-occultation measurements of the atmosphere, allowing the atmosphere to be viewed 'side on', thus enabling profile measurements of CO_2, H_2O ice and vapor in the Martian atmosphere. Preliminary instrument performance calculations of common measurement scenarios for the MOPA laser ASPEN instrument estimate the surface spot size at ~25m on the surface and a horizontal resolution of ~275m (similar to MOLA which was ~330m).

Multi-wavelength. In order to take advantage of the tremendous research and development that has gone into lasers and fiber optic components that operate in the near-IR *by the telecommunications industry* in recent years, the instrument will operate at wavelengths between 1.52 and 1.59 μm. These wavelengths are ideally suited to discriminate CO_2 and H_2O ices and vapor using the differential absorption lidar (DIAL) technique originally developed for terrestrial remote sensing [26, 27].

The Mars Science community has previously recognized the need for an ASPEN-type instrument. The need for actively scanning laser sensors that operate over a range of frequencies was acknowledged in the 2006 Solar System Exploration Roadmap [11] (page 108). In addition, the 2013 Mars Science Orbiter Science Analysis Group (MSO SAG) report stated that a "multibeam lidar" similar to the LOLA on LRO, and inheriting many aspects from the CALIPSO LIDAR, would "resolve optically dense atmospheric phenomena" and "significantly constrain seasonal mass budgets". In essence, it was thought to be an ideal instrument for a "2013 MSO mission" [12].

<u>Key Science:</u> Previous instruments have given glimpses of cloud and surface ice activity on Mars, but no previous Martian orbital instrument has been able to simultaneously address the following science measurements, which ASPEN would:

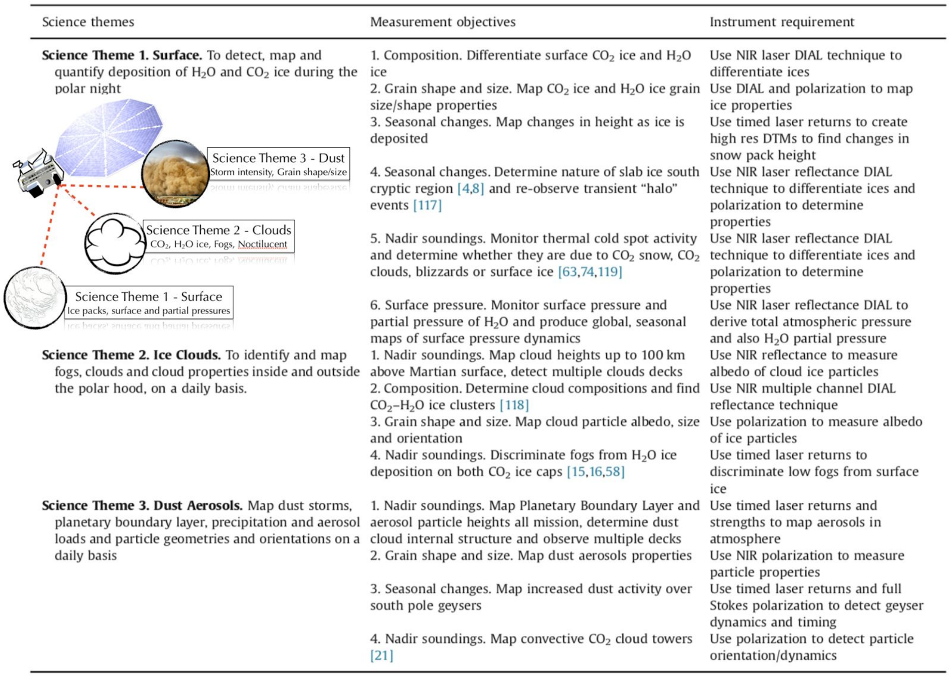
a.) Detect clouds up to 100km above the Martian surface during night and day;
b.) Discriminate between H_2O and CO_2 ice and dust on the surface and in aerosols in the atmosphere in both polar day and night [13];
c.) Map cloud structure using lidar backscatter and depolarization;
d.) Map large-grained (path length up to 30cm) CO_2 slab ice in the polar night, which is uniquely Martian and is extremely poorly understood [14];
e.) Determine whether the H_2O ice signature in the southern polar trough system is due to cloud [15] or surface ice [16];
f.) Monitor 'cold spot' activity during the polar night and determine whether these enigmatic features are due to CO_2 clouds, precipitation or surface ice [17,18];
g.) Monitor night and day gas/dust jet (geyser) activity within the 'Cryptic Region' (which have not yet been observed "in action") in southern late winter and early spring and determine what amount of solar energy is required for them to be active [8,19];
h.) Uniquely identify cloud types and platelet/grain orientation, in order to confirm the presence and structure of convective CO_2 cloud towers, a potentially critical part of the polar night dynamics and energy partitioning [20];
i.) Atmospheric column dust optical depths when instrument is in operation [21,22].
j.) Monitor the spring and summertime retreating polar caps for signs of sediment flows and possibly even geysers caused by subliming CO_2 ice. This type of activity has already been suggested to cause substantial changes mid-latitude gullies [23] and on dunefields [24].
k.) Address questions of spatial extent (locality and 'deep transport') of Martian cloud structure, which is anticipated to be on the order of 1km width and is crucial to understanding differences between terrestrial and Martian mesospheric dynamics [25].
i.) conduct a sensitive global (daytime and nighttime) search for outbursts of Martian methane down to 2ppb with relative errors of 0.5% [26,27].

3. Instrument Concept and Background

3.1 A conceptual model for energy transport in the Martian climate and why a lidar is essential to reveal it

Our understanding of the modern day Martian climate is based on relatively easy to visualize energy transport concepts. One can envisage the energy within the polar caps as governed by the latent heat of the ice in the caps, and can track the flow of ice from the caps to the atmosphere and mid latitudes during summer. These processes can be observed as the springtime recession of the seasonal cap, as the stored energy of the ice is broken up and moves into the atmosphere and the mid latitudes. Energy transport in the Martian climate has been tracked by telescopes and subsequent orbital instruments.

During winter, the reverse process is less certain, mainly because it can no longer be directly observed due to the onset of the polar hood and polar night [3]. It is during this time that the energy of the cap, like ice blocks in an igloo, is stored away again in the form of CO_2 and H_2O ice in the winter cap. However, this process is not well understood at all - we have some clues in the southern pole due to supercool spots that have been associated with CO_2 precipitation, and we know that during this time large blocks of CO_2 ice also form in order to create the araneiform terrain visible during springtime. However, their formation processes remain a mystery due to the inability of our passive imaging and spectroscopic instruments to pierce the cloudy enveloping veil. Further, it should be noted that radar instruments are generally not sensitive to the top 1mm-10cm of the ice, where the daily deposition and sublimation processes occur.



Science themes	Measurement objectives	Instrument requirement
Science Theme 1. Surface. To detect, map and quantify deposition of H_2O and CO_2 ice during the polar night	1. Composition. Differentiate surface CO_2 ice and H_2O ice	Use NIR laser DIAL technique to differentiate ices
	2. Grain shape and size. Map CO_2 ice and H_2O ice grain size/shape properties	Use DIAL and polarization to map ice properties
	3. Seasonal changes. Map changes in height as ice is deposited	Use timed laser returns to create high res DTMs to find changes in snow pack height
	4. Seasonal changes. Determine nature of slab ice south cryptic region [4,8] and re-observe transient "halo" events [117]	Use NIR laser reflectance DIAL technique to differentiate ices and polarization to determine properties
	5. Nadir soundings. Monitor thermal cold spot activity and determine whether they are due to CO_2 snow, CO_2 clouds, blizzards or surface ice [63,74,119]	Use NIR laser reflectance DIAL technique to differentiate ices and polarization to determine properties
	6. Surface pressure. Monitor surface pressure and partial pressure of H_2O and produce global, seasonal maps of surface pressure dynamics	Use NIR laser reflectance DIAL to derive total atmospheric pressure and also H_2O partial pressure
Science Theme 2. Ice Clouds. To identify and map fogs, clouds and cloud properties inside and outside the polar hood, on a daily basis.	1. Nadir soundings. Map cloud heights up to 100 km above Martian surface, detect multiple clouds decks	Use NIR reflectance to measure albedo of cloud ice particles
	2. Composition. Determine cloud compositions and find CO_2–H_2O ice clusters [118]	Use NIR multiple channel DIAL reflectance technique
	3. Grain shape and size. Map cloud particle albedo, size and orientation	Use polarization to measure albedo of ice particles
	4. Nadir soundings. Discriminate fogs from H_2O ice deposition on both CO_2 ice caps [15,16,58]	Use timed laser returns to discriminate low fogs from surface ice
Science Theme 3. Dust Aerosols. Map dust storms, planetary boundary layer, precipitation and aerosol loads and particle geometries and orientations on a daily basis	1. Nadir soundings. Map Planetary Boundary Layer and aerosol particle heights all mission, determine dust cloud internal structure and observe multiple decks	Use timed laser returns and strengths to map aerosols in atmosphere
	2. Grain shape and size. Map dust aerosols properties	Use NIR polarization to measure particle properties
	3. Seasonal changes. Map increased dust activity over south pole geysers	Use timed laser returns and full Stokes polarization to detect geyser dynamics and timing
	4. Nadir soundings. Map convective CO_2 cloud towers [21]	Use polarization to detect particle orientation/dynamics

Figure 1. ASPEN instrument science themes, measurement objective and instrument requirements [1].

3.2. Previous Lidar Mission – MOLA

The highly successful Mars Orbiting Laser Altimeter (MOLA) instrument on Mars Global Surveyor measured clouds and the height of the seasonal CO_2 surface ice accumulations [28,29]. However, its use of a single wavelength (1.064µm) prevented discrimination between H_2O and CO_2 clouds using the MOLA dataset. In addition, MOLA had no ability to assess particle sizes/shapes, nor measure H_2O or CO_2 gas vapor.

The MOLA instrument did demonstrate the ability to detect optically thin Martian dust devils [30,31]. Consequently, one can have confidence that ASPEN will be capable of monitoring dust loading and activity, including that associated with the eruption of 'geysers' in the south polar 'Cryptic' Region [8] - because the ASPEN detectors are designed not to saturate over the relatively high albedo Martian ice caps [32].

3.3. Previous Lidar Mission – Phoenix

The Phoenix spacecraft landed in the Vastitas Borealis region of Mars (at 68.2° N) in May 2008 and operated for 5 months or 152 Martian days (one summer and fall period) [33]. The Phoenix meteorology station included a vertical pointing Nd:YAG lidar operating at 1.064 and 0.532 µm. The lidar system successfully detected aerosol structures consistent with Martian cirrus clouds and in particular the 'virga' or "Mare's Tails" (ice particles falling from their formation site in the main cloud deck) as they passed over the lander during the local night [34]. Having no polarization capability, the Phoenix lidar could not directly determine grain shapes. We consider the Phoenix lidar to be a useful pathfinder for future lidar systems such as ASPEN.

3.4 Previous Terrestrial LIDAR mission - CALIPSO

The CALIOP laser onboard the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) space-craft was launched in April 2006 and is still in operation. With an orbit ~700 km, it is part of the 'A-Train' of Earth observing satellites. The CALIOP laser operates at 1.064 and 0.532 µm, measuring linear polarization in the latter band. The instrument was designed and tested at Ball Aerospace and is operated jointly by NASA and CNES [35].

The surface footprint of the CALIOP is ~100 m and the vertical resolution is 30–60 m. An example application of the CALIPSO instrument was observation of soot from Arctic wildfires drifting over Greenland [36]. The sensitivity to the aerosols associated with the fires provides a clear demonstration of lidar utility for monitoring/characterizing dust and cloud activity across multiple scales, as well as for studies of low lying fogs and sublimation flow events near the Martian surface. CALIPSO has also been used to monitor the height of the terrestrial planetary boundary layer, a useful precursor experiment for ASPEN at Mars. Although CALIOP does not exhibit the same wavelength flexibility and polarimetric capability (i.e. does not measure the full returned Stokes vector) of the ASPEN instrument, its enhanced abilities beyond the MOLA and Phoenix lidar provide further motivation for the concept of an orbital lidar at Mars.

4. Current TRL and Future technology advancement

The ASPEN concept is currently at TRL 2-3, with the initial designs and requirements laid out [1] and work on multiwavelength lasers [26]. Work on enabling technologies for variable frequency laser sources and detectors at GSFC has demonstrated the ability of measurement of CH_4 in the Earth's atmosphere using a wavelength manifold (rather than individual rotational lines) which has enabled accuracies of 0.5% [26]. In addition, work continues on a Martian wind-measuring LIDAR, called MARLI [37], which is complementary to the ASPEN concept. The MARLI design is a single wavelength approach that concentrates on atmospheric winds and dust and water ice clouds, in contrast to our multiwavelength, surface and atmosphere approach.

We anticipate a 3 year, $1 million project would get the instrument to TRL 4 with a breadboard done and retire much of the risk around the laser and amplifier. To advance the instrument from TRL 4 to TRL 6, with an instrument in a terrestrial airborne environment, would take roughly $3-5 million and a further 3-4 years of development. At that stage, the instrument could be proposed for future spaceflight missions.

5. Application to other planetary bodies

In this white paper, we have emphasized the utility of the ASPEN lidar instrument for an orbital Mars mission; however the same type of instrument would be applicable for a range of future missions. The multiwavelength polarization sensitive LIDAR would also provide invaluable insights when deployed to other rocky bodies, particularly those with seasonally changing (i.e. insolation driven) plumes of multiple icy volatiles, such as Enceladus, Triton, or Pluto, and insolation driven dust lifting, such as Ceres, Main Belt Comets and the Moon.

The ASPEN instrument concept would be ideal for missions to ice covered bodies (e.g. Europa, Enceladus, Triton, even methane ice on Kuiper Belt objects) to investigate the properties of icy surfaces in low sunlight conditions. As part of a Discovery class mission to active comet-like near Earth asteroids, the system would be ideal for probing the physical properties of a cometary coma. The instrument could also be used in an orbital mission to Venus,to probe cloud properties and structure in the NIR windows of the Venusian atmosphere.

6. Summary

We have outlined the scientific case for a polarization LIDAR for an eventual orbital mission to Mars. The combination of active, multiple-wavelength measurements with polarimetry makes this instrument concept an essential option in the future inventory of spacecraft instrumentation. The lessons learned from such an instrument would fundamentally advance our understanding of modern day volatile transport and deposition on Mars, and other planetary surfaces with insolation-driven volatile regimes.

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