A CubeSat mission for space-environment demonstration of Remote Laser-Evaporative Molecular Absorption (R-LEMA) spectroscopy sensor system concept


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ABSTRACT

Remote Laser-Evaporative Molecular Absorption (R-LEMA) spectroscopy is a NASA Innovative Advanced Concepts (NIAC) initiative to develop a sensor capable of remotely probing the molecular composition (as opposed to atomic composition) of cold solar system targets such as asteroids, comets and moons without significant atmospheres from a distant vantage. A continuous-wave laser heats a spot on the distant target; the heated spot forms a “backlighted” source through which the ejected plume is illuminated and target composition is determined from infrared molecular absorption lines. Theory and ongoing laboratory experiments indicate that the sensor concept is valid. To advance the system Technology Readiness Level (TRL), the concept must be demonstrated in the space environment. A formation-flying CubeSat experiment is proposed to demonstrate R-LEMA spectroscopy in the space environment. The main craft is equipped with a high-power laser, spectrometer and auxiliary subsystems necessary for executing the experiment. A second craft serves as target material, flying in formation at a specified distance from the main craft. This paper describes experimental objectives for a CubeSat experiment, including a 6U main craft and 3U target. In-orbit experiments are specified, and a supporting system architecture is derived from experimental objectives. A mechanical design is presented for both crafts, including all subsystem components required for the experiments. An execution sequence for in-orbit experiments is described.

Keywords: System analysis, Asteroid Composition

1. INTRODUCTION

1.1. Background

Current knowledge of asteroid composition comes mainly from observations of reflected light over optical and near-infrared wavelengths.1 Asteroids are classified within a taxonomy based on spectral characteristics of reflected solar light and thermal emission. The character of reflected or emitted light derives primarily from properties of surface material in the solid phase. Occasionally, bulk composition can be studied directly when meteorites are recovered, providing additional insight about composition of objects in the spectral class to which the parent asteroid belonged. For many asteroids, light reflected or emitted from the surface can only divulge information about surface material, which is often a fine dust coating (‘regolith’) that may or may not be derived from, or representative of, the asteroid’s bulk composition. Regolith may be altered material from the asteroid, it may be derived from collisions, or it may be some combination thereof.

Direct sampling of asteroid and comet material has been limited to a few missions. The Hayabusa mission by the Japanese Aerospace Exploration Agency (JAXA) collected and returned samples from the surface of asteroid 25143 Itokawa.2 The sample consisted of approximately 1 g of particles in the size range 10-100 µm, mainly from regolith. A second JAXA asteroid mission, Hayabusa2, arrived in orbit at asteroid Ryugu on 27 June 2018, and aims to collect subsurface material and return it to Earth. NASA’s Deep Impact mission to comet 9P/Tempel sought to excavate subsurface material by sending an impactor to the surface.3 Thermal emission spectra of the heated ejecta were obtained,
and analyzed for composition. NASA’s Stardust mission navigated through the coma of comet 81P/Wild, and returned samples to Earth. The European Space Agency’s (ESA) Philae lander of the Rosetta mission analyzed surface samples of comet 67P/Churyumov–Gerasimenko, sending data recorded in situ on the comet back to Earth. NASA’s Osiris-Rex mission, launched on 08 September 2016, aims to rendezvous with asteroid 101955 Bennu, perform a ‘touch-and-go’ maneuver, and then return surface material samples to Earth.

1.2. R-LEMA Concept

Missions to directly assess asteroid composition are notable for their ingenuity and tenacity in the face of very difficult mission scenarios. Due to overall mission complexity, sample-return or landing/in situ measurement missions are likely to be limited in scope and number for the foreseeable future. We propose a novel method for directly probing the molecular composition of cold solar system targets (asteroids, comets, planets, moons) from a distant vantage, such as from a spacecraft orbiting the object. The spacecraft includes a solar-powered laser array. A directed energy beam from the laser is focused on the target. With target flux in the range of ~10 MW/m², the spot temperature rises rapidly, to ~2500 K for rocky targets, and melting and evaporation of surface materials on the target occurs. Material ejected from the heated spot creates a molecular plume of surface materials in front of the spot. Energy from the laser is insufficient to dissociate molecules or spawn significant ionization, so the plume retains the molecular composition of the target. The melted spot becomes a high-temperature blackbody source. As the blackbody radiation passes through the ejected plume, molecular and atomic absorption occur in the plume materials. Bulk molecular and atomic composition of the surface material is investigated by using a spectrometer to view the heated spot through the ejected material. A system concept is shown in Fig. 1. The intended system function can be summarized by the designation Remote Laser-Evaporative Molecular Absorption (R-LEMA) spectroscopy.

1.3. Comparisons to Existing Methods

The R-LEMA tactic differs fundamentally from current approaches for ‘remote’ composition analysis. One currently used approach is Laser-Induced Breakdown Spectroscopy (LIBS). This technology has been thrust into the public consciousness due to deployment of the ‘ChemCam’ LIBS instrument on the Mars Curiosity rover. ChemCam uses a pulsed laser with optics that can focus on targets within ~10 m of the rover. The laser pulses deliver a flux exceeding 10 TW/m², which is sufficient to dissociate molecules and create an atomic plasma from materials in the solid target. Light emitted from the plasma is delivered to a series of three spectrometers covering the range 240-850 nm. Atomic composition is derived from optical emission lines in the recorded spectra.

Figure 1. R-LEMA system concept for probing bulk molecular and atomic composition of cold solar system targets, such as asteroids, comets, planets, moons, from a distant vantage, such as from a spacecraft orbiting the object.
Curiosity rover is limited by laser power, and by the strength of characteristic emission from the plasma. Operating at greater distances would require larger lasers and more sensitive spectral detection systems. Additionally, LIBS performs atomic composition analysis by observing characteristic emission spectra from the plasma in visible and near-infrared (Vis/NIR) wavelengths.

Laser-Induced Thermal Emission (LITE) spectroscopy is also capable of probing molecular composition from moderate distances.\(^6\) LITE uses a relatively low-power laser to heat materials in the target to a temperature that is perceptibly higher than the environment. An infrared imaging system focuses the target on an infrared spectrometer. Materials in the target emit blackbody radiation with diagnostic spectral features in infrared wavelengths that arise from rotational and vibrational movements of molecules. LITE spectroscopy is theoretically capable of operating at very large stand-off distances, limited mostly by laser power. LITE spectroscopy is typically limited to molecular composition analysis, due to low emitted signal in optical wavelengths, where characteristic emission occurs. A strategy similar to LITE was utilized by the Deep Impact mission.\(^7\) A large amount of material was ejected from the comet by the impact. The cloud of ejected debris was pushed by solar radiation pressure into the comet’s coma. The ejected material is heated by solar radiation (rather than a laser) to \(\sim 235\) K, and the heated material then emits blackbody energy peaking near 12 \(\mu\)m. ‘Solar-illuminated emission spectra’ in the range 5.2-38.0 \(\mu\)m were recorded from the Spitzer Space Telescope in low-Earth orbit, at a distance of \(\sim 0.75\) AU from the comet. Molecular composition of materials in the coma was inferred from the mid- and long-wave infrared (MWIR and LWIR) spectra. These examples illustrate some of the various methods that can be used to exploit light-matter interaction for purposes of target composition analysis; a general depiction is shown in Fig. 3.

Figure 2. The complementary nature of LIBS and R-LEMA approaches is illustrated by the unique sensing methods utilized by each system.

LIBS seeks to determine atomic composition by observing characteristic emission lines in a plasma created from target surface material. The LITE scenario probes molecular composition using infrared emission of target surface material in solid phase. Whereas, R-LEMA intends to measure infrared absorption within a vapor. Infrared emission and absorption spectra of the same (solid) material should correspond closely. However, infrared emission spectra of a solid material and infrared absorption of the same material in gas phase may display some unique features. For example, Raman scattering likely results from differing physical processes in solids and liquids, which could produce differences in an absorption spectrum compared to an emission spectrum of the same material. It is conceivable that some rotational absorption lines may appear in gas phase that are not possible when the same molecules are bound in a solid. Additionally, R-LEMA is capable of exploring shallow sub-surface materials, by excavating a local area to bore deeper into the target. Laboratory experiments demonstrate the ability of a directed-energy beam to bore into a narrow spot on
the target, even at \( \sim 10 \text{ MW/m}^2 \), showing promise for R-LEMA to explore shallow sub-surface profiling of target molecular composition.

R-LEMA may also have a range advantage over LIBS, based on two factors. Both sensor systems rely on light sources that originate at the target. LIBS relies on atomic emission from the plasma, which is inherently faint even when the impinging laser flux is high. Light produced by the remote plasma must be of sufficient power when sampled by an optical spectrometer, potentially creating a range limitation for LIBS. The source light for R-LEMA is thermal emission from the heated spot, created with \( \sim 10 \text{ MW/m}^2 \) from the laser. A larger spot radius with the requisite energy will provide more power to the remote sensor system. Thermal emission created by the heated spot is more than sufficient for distant viewing, and flux available to the spectrometer is not a limiting factor for molecular composition analysis. The second factor relates to the laser flux required at the target. For a distant target, a LIBS laser must deliver \( \sim 10 \text{ TW/m}^2 \) to the target in order to create a plasma, limiting the operational distance of a LIBS system. Lower flux requirements mean that R-LEMA will operate at much greater distances for a given laser power. The noted differences highlight the complementary nature of LIBS and R-LEMA systems; indeed, suitable side-by-side sensors could probe the same target to provide a more complete assessment of target composition.

### 1.4. Roadmap to R-LEMA Mission Readiness

R-LEMA spectroscopy concept development is supported by a NASA Innovative Advanced Concepts (NIAC) initiative. The NIAC program supports nascent technology that shows promise for “changing the possible” in space exploration. Phase I efforts attained theoretical results that indicate the R-LEMA system concept is viable. Phase II efforts are ongoing, with a goal of advancing the Technology Readiness Level (TRL) of the sensor system concept. Laboratory experiments are progressively demonstrating the intended functionality with existing, benchtop technology. The next phase of development will require that the system be demonstrated in the space environment. The benchtop setup must be re-envisioned for deployment on a spacecraft, and in a scenario that can demonstrate the technique’s promise for remote molecular composition analysis. This paper describes an experiment using two CubeSats to test the R-LEMA system in low-Earth orbit, depicted in Fig. 3. In the envisioned experiment, the main craft is a 6U CubeSat containing the R-LEMA system, including laser, spectrometer and support systems. A second 4U CubeSat contains target materials that are to be interrogated by the R-LEMA system on main craft. The two craft orbit in formation while tests of the R-LEMA system are performed.

![Figure 3. Depiction of formation flying experiment to test the R-LEMA concept in low-Earth orbit. The main craft contains a laser directed at the target craft. A spectrometer aboard the main craft views the heated spot to probe the composition of a target panel.](image-url)
2. MISSION ANALYSIS

2.1. Mission Scenario and Goals

The main goal of the mission is to provide a space-environment test of the R-LEMA spectroscopy sensor system. The main craft and target fly in formation, providing an offset distance to verify remote operation. No specific orbit is required, other than to remain aloft for a sufficient time to complete sensor system trials, estimated to be a minimum of 3 months. Deployment from the International Space Station (ISS) would be ideal. While in orbit, multiple tests of the sensor system would be executed. Known materials on the target craft would be interrogated by the R-LEMA sensor, and compositional determinations would be evaluated. Design performance, such as pointing accuracy, thermal control, and distance limits can also be judged.

A secondary goal of the mission will be to measure the thrust produced by the plume ejection. With no modifications whatsoever, the R-LEMA sensor system can be employed to modify the target’s trajectory. The dual capability has potential benefits for altering asteroid orbits, such as to divert a potential Earth impact, or to move an asteroid into an accessible ‘outpost’ orbit for simplified access to resources. During the experiment, the two craft will fly in close proximity, requiring guidance, navigation and control (GNC) capability. As the R-LEMA laser is active, a reactionary thrust will be produced as material is evaporated from the target. The GNC system will detect the change in relative position as the reactionary thrust moves the crafts apart, and the magnitude of the reactionary thrust can be reckoned. Theoretical predictions and laboratory experiments suggest that reactionary thrust from laser ablation is expected to be on the order of 100 μN/W_{optical}. To date, the ground-based results have not been confirmed in the space environment.

Space-based lasers are also envisioned as a propulsion source for small spacecraft with reflective sails. As the laser beam is reflected off the sail, a reactionary thrust is imparted to the craft. A third potential goal of the mission could be to measure the thrust produced by reflecting the laser beam from a mirror on the target craft. The reactionary force produced by reflection is proportional to the flux, but inversely proportional to the speed of light. Any measurement of reactionary thrust would require sensitive determination of relative position. A reactionary thrust is also created as the laser energy is emitted from the main craft, increasing the relative motion that must be discerned by the GNC system that would be required for a thrust estimate. Since laser power will be relatively low compared to envisioned photonic propulsion systems, measurements of thrust due to laser reflection would be challenging.

2.2. System Requirements and Constraints

2.2.1. Laser and Associated Optical System

The main craft will contain the R-LEMA spectroscopy sensor system. The system requires a high-power laser with associated optics capable of producing a collimated beam that delivers ~10 MW/m² to a spot of maximum possible size on the target which will lie at a specified distance for the experiment. The baseline experiment consists of a 1 cm spot diameter full-width half maximum (FWHM), with an initial stand-off distance of 10 m. The experiment will move the target craft to successively greater distances. The optics should produce a collimated beam with the required flux, so that no focusing of the laser beam is required as the distance to the target changes. The laser beam must be directed at the target, with pointing accuracy sufficient to localize the beam within a relatively coarse area on the target craft. The target material will be placed within one 1 cm by 1 cm face on the target craft, and the beam should be capable of pointing to quadrants within the face. The more demanding pointing requirement will be to limit the beam motion across the surface of the target to less than one spot radius per second. If the beam moves across the target at a higher rate, then the dwell time will be insufficient for melting and evaporation of rocky targets. For a target at 10 m and a spot diameter of 1 cm, the pointing jitter should be less than 0.5 cm/s drift on the target surface. As the target is moved away, the angular pointing requirement becomes smaller. The experiment should seek to test the sensor system at distances up to 100 m.

The laboratory system utilizes a continuous wave (CW) laser fiber amplifier. The fiber amplifier is pumped by a diode laser at 976 nm. The laser amplifier output at 1064 nm produces a high beam quality. Furthermore, the high power-to-mass ratio of fiber amplifiers, now exceeding 1 kW/kg, implies many advantages for the proposed mission. A diode laser without fiber amplification could also be considered, but lower beam quality would place additional constraints on the optical system. A candidate laser and optical system based on a diode laser is described in accompanying papers.
2.2.2. Spectrometer and Associated Optical System

The R-LEMA sensor system requires a high-resolution spectrometer, with associated optical components that couple sufficient thermal energy from the heated spot into the spectrometer. The laboratory prototype system uses a Bruker Vertex-80 FT-IR spectrometer, with spectral resolution of 0.08 cm\(^{-1}\) and spectrum acquisition time of ~0.3 s using a HgCdTe (MCT) cooled detector. Operating specifications of the laboratory model are more than adequate for molecular composition analysis. Space constraints on the 6U CubeSat frame will limit the spectrometer capabilities for a deployed system. Space constraints may preclude the use of an FT-IR spectrometer in favor of more compact dispersive designs. A trade study for the spectrometer characteristics is provided in accompanying papers.\(^{25}\)

The main purpose of the optical system is light gathering; no requirement for imaging is envisioned for the first iteration of space environment testing. The spectrometer detector characteristics will drive requirements for light gathering. The heated spot is essentially a point source located at a significant distance from the R-LEMA spectrometer. The telescope should have a very narrow field of view, as well as the capability to focus on the target as the distance varies. Telescope system aperture will be limited by the size of one CubeSat frame, suggesting a need for some real ingenuity in the optical design.

2.2.3. Attitude and Relative Position Control

To execute the envisioned experiments, the two spacecraft must fly in formation, maintaining a precise relative position throughout the mission. A mechanism for determining relative position in near real-time is required, either with passive devices (e.g., cameras), active devices (e.g., laser ranging, etc.) or a combination of active and passive schemes. The target craft should maintain a constant attitude relative to Earth, and the main craft should maneuver to keep a constant relative position. Precision requirements are driven in part by laser pointing, but requirements for achieving thrust estimates should also be considered. An approach for attitude and relative position control is presented in accompanying papers.\(^{25}\)

2.2.4. Electrical Power

An Electrical Power Subsystem (EPS) will be required for generating, conditioning, regulating, managing and storing of power for peak demand and supplying it to the spacecraft subsystems. The main components of the EPS include: solar panels, batteries and the Power Distribution Unit (PDU). Solar panels are used to generate power from the sun. The setting of a 200 W laser in a 6U CubeSat implies several design difficulties. Power for CubeSat operation is supplied by a 3.7 V battery bank. Using a low-voltage battery to power the laser would far exceed current limits of the batteries. One alternative design would utilize a dedicated high-voltage circuit to supply the laser; the architecture is described in detail in accompanying articles.\(^{26}\)

2.2.5. Thermal Control

Controlling the temperature distribution throughout the satellite frame will be essential for electronic components operation and consequently mission success. Due to the absence of atmosphere, the space environment exposes satellites to extreme temperature conditions through an orbit. Furthermore, the high-power laser and auxiliary components will generate a significant amount of waste heat that must be redirected and dissipated to prevent overheating of components. The expected temperature distribution within the spacecraft frame while in orbit will inform the design of sufficient thermal control devices, avoiding high temperature gradients that could lead to component failure. Preliminary analysis for temperature range on orbit are outside the suggested operating ranges provided by component manufacturers.\(^{27,28}\) Mechanical design must include a network of heat pipes and passive radiative surfaces for heat distribution and expulsion.

2.2.6. Communications

Ground communications will be required for the main craft. Command and control of experiments will be executed from the ground. Primary science data (spectra) and spacecraft telemetry will be transmitted to the ground for analysis. For the first iteration of experiments, no image data will be collected for scientific analysis, although telemetry could include images for relative position algorithms. As such, the data volume for ground transmission is not expected to tax the standard low-fidelity CubeSat ground communication system.\(^{29}\) Electronic storage of science and telemetry data will be required to bridge gaps in ground communication. In addition to ground communications, a link between the main craft and the target will be required for coordination of experiments.
3. **SUBSYSTEM ARCHITECTURE**

3.1. **Mechanical Design**

CubeSat standard components available as off-the-shelf items will serve for the majority of subsystem components. The exceptions are the laser, spectrometer, and thermal control apparatus. Based on the preliminary requirements for the experiment, an initial mechanical design demonstrates that a 6U CubeSat frame is sufficient for housing all required components, illustrated in Fig. 4.

![Diagram of main craft frame with many off-the-shelf CubeSat components.](https://example.com/diagram)

**Figure 4.** Depiction of main craft frame with many off-the-shelf CubeSat components. The laser being considered is a 200 W diode laser, with space allocated for thermal control apparatus. The spectrometer is a compact FT-IR design from Bruker.

3.2. **Operations**

Experiment execution will be coordinated by a combination of ground commands and automated, on-board control. The general cadence of experiments is expected to entail short bursts of CW laser energy, lasting from 10-30 s, followed by intermission times of ~10 minutes to allow redistribution and dissipation of heat. Execution of an experiment will consist of a series of checks to establish system readiness:

a. Temperature:

a.1. The motherboard polls thermocouples around the main craft. The motherboard compares the received values with values from each component operation range and makes a readiness determination. If the temperature of a component is higher than its operating range, the experiment will be postponed until an acceptable value is received. The temperature of all components are monitored constantly and the experiment will only occur when all of them are inside the operation range.

b. Position:

b.1. Main craft in relation to the target: the system position will be determined on the 6 axes constantly in the following order:

b.1.1. The main craft’s motherboard will send a Wi-Fi signal so that the target’s motherboard send data from target’s accelerometer to the main craft, also by Wi-Fi signal. Using values from both accelerometers, the main craft motherboard will be capable to determine relative position on 3 axis of rotation and then send a Wi-Fi signal so that the target’s motherboard send digital signal to the reaction wheels to adjust the main craft position.

b.1.2. The main crafts motherboard will process the image data received by the main craft’s camera that will find the target using algorithms to determine the relative position of the target within the camera’s field of vision, and will send Wi-Fi signals to the target’s motherboard, so that the relative position of the two space ships are adjusted.
b.1.3. When the relative position of the two crafts are defined by the 3 rotation axis and in the camera field of view, the motherboard will operate a distance sensor IR focusing in an specific region from the target, determining the 6th degree of freedom of the system.

b.2. Main craft in relation to the Sun: The motherboard tells the CubeSense to send a analogic signal, that will be converted to digital by an ADC then sent to the reaction wheels, so that the target is always in one side of the mother ship and the sun on the other.

b.3. Mother ship in relation to the Earth: The motherboard compares the values from the GPS sensor with the pre-determined values from the orbit and, if needed, tells the propulsion system and the reaction wheels to correct the orbit.

c. Energy:

The mother ship supply energy to the battery indicator that are connected to the batteries and receives analog signal, that will be converted in digital by an ADC, the motherboard then compares the received values with the pre-defined ideal values. If the batteries don’t have enough power, the motherboard unleashes the power supply from the PDU’s to the batteries until these have enough charge for the experiment to run.

d. Experiment:

d.1. Laser: the motherboard tells the PDU to send power to the laser and asks the laser to send a signal via serial communication to confirm that it received the power. Then it sends a signal, also via serial communication, to turn on the laser, waits the required time, sends another signal to turn off the laser and tells the PDU to stop supplying energy to the laser.

d.2. Spectrometer: The motherboard tells the PDU to supply power to the spectrometer and asks the spectrometer to send a signal via serial communication to confirm that it received the power. Then It sends a signal, also via serial communication, to turn on the spectrometer, waits the required time, sends another signal to turn off the spectrometer and tells the PDU to stop supplying energy to the spectrometer.

d.3. Data storage: The motherboard tells the spectrometer to send the data via serial then it is stored temporarily in a SD card.

d.4. Data communication: When the mother ship’s position in relation to the Earth matches the receiving antennas’ range, the motherboard will tell the PDU to supply power to the RF antenna, tells the antenna via serial communication to send a received power confirmation signal and then sends a signal to communicate with the base located in the Earth. Then the motherboard sends the data stored in the SD card via antenna RF and, after all the data is transferred, deletes the data saved in the SD Card.

4. CONCLUSIONS

The R-LEMA spectroscopy sensor system is a concept being supported by a NIAC initiative. Theoretical results obtained in the Phase I NIAC indicate that the R-LEMA system concept is viable. Laboratory experiments are ongoing as part of the Phase II NIAC. To advance the system TRL, a space environment demonstration is required. This paper describes an experiment to test the R-LEMA system using two CubeSats flying in formation in low-Earth orbit. In the envisioned experiment, the main craft is a 6U CubeSat containing the R-LEMA system, including laser, spectrometer and support systems. A second 4U CubeSat contains target materials that are to be interrogated by the R-LEMA system on main craft. The two craft orbit in formation while tests of the R-LEMA system are performed.

A secondary goal of the mission will be to measure the thrust produced by the plume ejection. As the R-LEMA laser is active, a reactionary thrust is produced by material evaporating from the target. The GNC system will detect the change in relative position as the reactionary thrust moves the crafts apart, and the magnitude of the reactionary thrust can be reckoned. A third potential goal of the mission could be to measure the thrust produced by reflecting the laser signal from a mirror on the target craft, although precise GNC apparatus would be required.

A system architecture for the 6U main craft has been outlined. Preliminary requirements for laser, spectrometer and auxiliary systems have been described. An initial mechanical design based on CubeSat industry standard components has been developed for the main craft. A preliminary experimental sequence was presented that is capable of achieving the mission objectives.
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