Distributed CubeSat Spectroscopy Network for Martian Surface and Atmospheric Analysis

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Abstract

This paper introduces a distributed CubeSat-based spectroscopy network designed for comprehensive analysis of the Martian surface and atmosphere. The mission deploys a constellation of 20 CubeSats, each equipped with either an ultraviolet-visible (UV-Vis) spectrometer (200–700 nm) or an infrared (IR) spectrometer (0.7–10 µm), to perform high-resolution, multi-wavelength spectral mapping. The network targets the detection of hydrated minerals, carbonates, sulfates, and silicates via IR spectroscopy, and organic molecules, oxides, and volatiles through UV-Vis spectroscopy. Integrated with the Chameleon SWIR camera system, the constellation enables real-time tracking of atmospheric dust and clouds, facilitating adaptive mission operations. Orbiting at an altitude of 175 km with a corrected orbital velocity of approximately 3.465 km/s, the CubeSat network achieves a full spectral scan of Mars within three days, offering superior coverage and revisit rates compared to traditional single-orbiter missions. Data is processed onboard and transmitted using X-band or Ka-band frequencies to relay orbiters or directly to Earth. Following the primary surface mapping phase, the CubeSats transition to an extended mission, focusing on atmospheric monitoring, climate analysis, and trace gas detection. A subset of the constellation will also serve as a real-time weather tracking and communications relay system for future Mars missions, enhancing operational longevity. This pioneering CubeSat spectroscopy network demonstrates a scalable, cost-effective approach to planetary remote sensing, with potential applications extending to lunar, asteroid, and exoplanetary exploration.

Nomenclature

H = Orbital altitude (km)

R = Orbital radius (km)

V = Orbital velocity (km/s)

T = Orbital period (s)

Sw = Swath width (km)

N = Number of CubeSats

Λ = Wavelength (nm or µm)

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I. Introduction

Planetary exploration has traditionally relied on single-orbiter spacecraft equipped with either infrared (IR) or ultraviolet-visible (UV-Vis) spectrometers to investigate Martian surface composition and atmospheric properties. Missions such as Mars Global Surveyor with its Thermal Emission Spectrometer (TES) [1] and Mars Reconnaissance Orbiter with its Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) [2] have demonstrated the value of these instruments, yet their single-platform design limits spectral range, revisit frequency, and dataset completeness. IR spectrometry excels at identifying mineralogical features like silicates and sulfates, while UV-Vis spectrometry is adept at detecting organic compounds and volatiles critical for habitability studies [3]. The M-STAR (Mars Spectroscopy and Tracking for Atmospheric Research) mission integrates these complementary capabilities within a distributed network of 20 CubeSats, enhancing data resolution, planetary coverage, and mission redundancy. This paper details the mission's design and implementation, drawing on established technologies to provide a practical, cost-effective solution for Mars exploration.

II. Mission Overview

The M-STAR mission deploys a constellation of 20 CubeSats into a polar sun-synchronous orbit at 175 km altitude, with an orbital velocity of 3.465 km/s, calculated using Mars' gravitational parameter $\mu = 4.2828 \times 10^{13}\ \frac{m^3}{s^2}$ and orbital radius r=3,565 km [19]. Each CubeSat is equipped with either a UV-Vis spectrometer (200–700 nm) or an IR spectrometer (0.7–10 µm), enabling simultaneous, high-resolution spectral mapping across multiple wavelengths. This dual-wavelength approach, inspired by missions like CRISM [2] and New Horizons' ALICE [3], detects silicates, carbonates, sulfates, and hydrated minerals (IR), alongside organic molecules, oxides, and volatiles (UV-Vis). In Phase 1, lasting three days, the network completes a full spectral scan of Mars' 144.8 million km² surface, utilizing 25 km-wide swaths and leveraging multiple orbital passes and Mars' rotation to achieve enhanced coverage and revisit rates compared to conventional single-orbiter missions [4]. The Chameleon SWIR camera system provides real-time dust and cloud tracking, enabling adaptive observation strategies based on Martian weather conditions, a technique adapted from Earth-based remote sensing [5].

Data is processed onboard and transmitted via X-band or Ka-band frequencies to relay orbiters, such as the ExoMars Trace Gas Orbiter [6], or directly to Earth, building on communication strategies from Mars Odyssey [7]. After the 3-day Phase 1, the CubeSats enter Phase 2, an extended mission phase lasting approximately five years, based on typical CubeSat durability in Mars' environment [8]. During Phase 2, the spectrometers are repurposed for long-term atmospheric monitoring, climate analysis, and trace gas detection, while a subset of CubeSats serves as a real-time weather tracking and communications relay system for future Mars missions, extending operational utility akin to MarCO's relay functions [9]. This dual-phase mission, Phase 1: 3 days, Phase 2: ~5 years, maximizes the CubeSats' estimated 5-year lifespan, offering a scalable, cost-effective framework for planetary remote sensing with applications beyond Mars, including lunar, asteroid, and exoplanetary studies.

III. Instrumentation and System Design

The M-STAR mission deploys a constellation of 20 CubeSats to perform high-resolution spectral mapping of Mars' surface and atmosphere, leveraging miniaturized optics and distributed sensing. Each CubeSat carries either an ultraviolet-visible (UV-Vis) spectrometer (200–700 nm) or an infrared (IR) spectrometer (0.7–10 µm), building on proven designs such as ALICE [3] and the Thermal Emission Spectrometer (TES) [1]. This section details the instrumentation and system design, emphasizing their application across two mission phases: surface mapping and atmospheric monitoring.

A. UV-Vis Spectrometer System

1. Design and Specifications

The UV-Vis spectrometer captures reflected solar radiation in the 200–700 nm range to detect organic molecules, oxides, and volatiles. Drawing from ALICE on New Horizons [3] and Juno-UVS [10], it features a compact Cassegrain optical system with a high-efficiency diffraction grating and a back-illuminated CCD or CMOS detector for enhanced UV sensitivity. A tunable filter isolates specific wavelengths, while adaptive optics correct for pointing inaccuracies, ensuring a high signal-to-noise ratio (SNR) under Martian conditions [11]. Calibration uses onboard reflectance standards and dark current measurements, adapted from ALICE [3]. Power consumption is 10–15 W, supported by solar panels and lithium-ion batteries, with data compressed onboard and transmitted via X-band or Ka-band to relay orbiters like the ExoMars Trace Gas Orbiter [6].

2. Application in Phase 1: Surface Mapping

In Phase 1, the UV-Vis spectrometers map the Martian surface from a 175 km polar sun-synchronous orbit at 3.465 km/s, scanning 25 km-wide swaths to achieve global coverage in three days. The system targets organic compounds (e.g., polycyclic aromatic hydrocarbons), oxides (e.g., hematite), and volatiles (e.g., adsorbed water), complementing IR mineral data. Integration with the Chameleon SWIR camera [5] enables real-time dust and cloud tracking, prioritizing clear regions, akin to CRISM's adaptive mineral mapping [2].

3. Application in Phase 2: Atmospheric Monitoring

In Phase 2, the spectrometers shift to atmospheric monitoring, measuring scattering, aerosols, and trace gases (e.g., ozone) within the 200–700 nm range. The high-sensitivity detector tracks subtle variations, while a subset of CubeSats adjusts orbits to relay data for future missions. This repurposing mirrors Maven's Imaging Ultraviolet Spectrograph (IUVS) [12], enhancing M-STAR's climate analysis capabilities.

B. IR Spectrometer System

1. Design and Specifications

The IR spectrometer operates in the 0.7–10 μm range, detecting thermal emissions and reflected light to identify silicates, carbonates, sulfates, and hydrated minerals. Inspired by TES [1] and the Planetary Fourier Spectrometer (PFS) [13], it employs a cooled detector to reduce thermal noise, a tunable filter for wavelength isolation, and adaptive optics for distortion correction. Calibration uses onboard blackbody targets and dark current measurements, adapted from TES [1]. Power (10–15 W) and data transmission align with the UV-Vis system, utilizing relay orbiters for downlink [6].

2. Application in Phase 1: Surface Mapping

In Phase 1, the IR spectrometers map the surface from the same 175 km orbit at 3.465 km/s, scanning 25 km swaths for global coverage in three days. The system detects mineralogical signatures of past water activity (e.g., clays, sulfates), building on CRISM's mapping of Mawrth Vallis [2] and TES's olivine studies [1]. The Chameleon SWIR camera [5] supports adaptive scanning during clear conditions.

3. Application in Phase 2: Atmospheric Monitoring

Following the 3-day Phase 1, the IR spectrometers transition into Phase 2, utilizing the ~5-year remaining lifespan to monitor atmospheric thermal emissions from the 175 km orbit at 3.465 km/s. The system shifts from surface analysis to tracking dust storm propagation, water vapor gradients, and temperature fluctuations, adjusting the tunable filter to prioritize mid-infrared bands (e.g., 4.3 μm for CO_2, 6–7 μm for H_2O) where atmospheric features are most prevalent [13]. The cooled detector sustains sensitivity to faint signals like ice cloud emissions, despite long-term radiation exposure [8], while onboard software reconfigures to emphasize temporal sampling, capturing diurnal dust and thermal cycles over the extended period. A subset of CubeSats elevates to slightly higher orbits (e.g., 200–250 km) to serve as relays, using X-band or Ka-band links [6] to support future missions, aligning with EMIRS's atmospheric monitoring approach [14] and enhancing M-STAR's contribution to climate studies.

IV. Data Collection and Analysis

The M-STAR mission employs a network of 20 CubeSats to acquire and process high-resolution spectral data from Mars' surface and atmosphere, utilizing ultraviolet-visible (UV-Vis) and infrared (IR) spectrometers. This section details the data acquisition strategy, onboard processing, transmission architecture, and scientific interpretation, ensuring comprehensive planetary coverage across the 3 day Phase 1 surface mapping and the ~5 year Phase 2 atmospheric monitoring.

A. UV-Vis Spectral Data Collection and Analysis

1. Acquisition Strategy

Each UV-Vis spectrometer (200–700 nm) captures reflected solar radiation and scattered atmospheric light, detecting organic molecules (e.g., polycyclic aromatic hydrocarbons, perchlorates), oxides (e.g., Fe^{3+} compounds like hematite), and volatiles (e.g., adsorbed water) [3]. Operating in a 175 km polar sun-synchronous orbit at 3.465 km/s, the CubeSats scan 25 km-wide swaths, achieving global coverage of Mars' 144.8 million km^2 surface in three days [4]. A variable duty cycle balances power and storage, with continuous acquisition during daylight passes (~60% of each 116-minute orbit) and calibration during dark-side operations using dark current correction, adapted from ALICE [3].

3. Transmission and Interpretation

Compressed data is transmitted via X-band (100–250 kbps) or Ka-band to relay orbiters like the ExoMars Trace Gas Orbiter [6] or Earth, generating ~500 MB daily across the network. Downlinked data is correlated with CRISM [2] and rover datasets (e.g., Curiosity's ChemCam [16]), enabling real-time adaptations like targeted scans of organic-rich regions, enhancing Phase 2's atmospheric studies.

B. IR Spectral Data Collection and Analysis

1. Acquisition Strategy

Each IR spectrometer (0.7–10 μm) collects thermal emissions and reflected IR data to identify silicates, carbonates, sulfates, and hydrated minerals, critical for understanding Mars' geological and water history [1]. Orbiting at 175 km with a 3.465 km/s velocity, IR CubeSats complement UV-Vis swath coverage, mapping the surface in three days. Data acquisition mirrors the UV-Vis duty cycle, collecting during daylight (~60% of orbit) and calibrating on the dark side with blackbody calibration, as proven by TES [1].

2. Onboard Processing

Preprocessing corrects thermal noise and atmospheric interference using baseline subtraction and blackbody standards [1]. Spectral deconvolution, inspired by CRISM [2], resolves overlapping mineral bands, with adaptive binning and wavelet compression reducing data to 15 MB per orbit, aligning with UV-Vis efficiency [15]. This streamlined approach supports the mission's extended duration.

3. Transmission and Interpretation

IR data is transmitted via X-band or Ka-band, leveraging relay precedents like EMIRS [14], with a network total of ~500 MB daily. Analysis cross-validates with TES [1], CRISM [2], and THEMIS [17] datasets, supporting Phase 1 mineral mapping and Phase 2 atmospheric monitoring (e.g., dust storms, water vapor), enhancing real-time science applications like landing site selection.

2. Onboard Processing

Raw data undergoes real-time preprocessing to correct noise, background contamination, and solar angle variations, employing dark current subtraction, flat-field correction, and stray light filtering, methods refined by Juno-UVS [10]. Feature extraction uses Principal Component Analysis (PCA) for spectral encoding, adaptive binning to retain high-resolution data in key regions, and wavelet-based compression, reducing data volume by ~70% to 15 MB per orbit [15]. This efficiency supports frequent transmissions within the 10–15 W power budget.

V. Expected Scientific Impact

The M-STAR mission leverages a distributed CubeSat network to advance planetary science and support human exploration of Mars through dual-wavelength spectroscopy. Operating UV-Vis (200–700 nm) and IR (0.7–10 μm) spectrometers across 20 CubeSats, it builds on historical missions like Mars Reconnaissance Orbiter (MRO) [2] and Mars Global Surveyor (MGS) [1], enhancing spatial and temporal resolution over single-orbiter designs. This section outlines the mission's contributions to surface composition analysis, atmospheric studies, and resource mapping, emphasizing its role in enabling sustained human presence.

A. UV-Vis Contributions

1. Surface Composition and Habitability

The UV-Vis spectrometer detects organic molecules (e.g., polycyclic aromatic hydrocarbons, perchlorates), potential biosignatures tied to biological activity [2], and oxidized minerals (e.g., Fe^{3+} oxides like hematite) indicating past water activity [3]. It also tracks volatile surface coatings (e.g., adsorbed water, frost), revealing seasonal atmospheric interactions [11]. These measurements, conducted during the 3-day Phase 1 mapping from a 175 km orbit at 3.465 km/s, identify astro-biologically significant regions, building on ALICE's volatile detection [3].

2. Atmospheric Chemistry and Climate

In Phase 2's ~5-year duration, the UV-Vis system monitors atmospheric composition, tracking dust storm evolution, aerosol scattering, and trace gases (e.g., ozone, sulfur dioxide) [12]. Real-time data improves climate models by characterizing dust impacts on solar radiation and surface heating, critical for predicting weather patterns and storm severity for future missions [7]. This capability extends Maven IUVS's atmospheric insights [12].

3. Human Exploration Support

UV-Vis data maps water ice and perchlorates, vital for in-situ resource utilization (ISRU) like fuel production and life support [2], while identifying iron oxides for construction [1]. It assesses dust-storm-prone areas and UV reflectance for radiation shielding, enhancing entry, descent, and landing (EDL) safety [11], aligning with NASA's Artemis goals [18].

B. IR Contributions

1. Surface Composition and Resources

The IR spectrometer identifies silicates, carbonates, sulfates, and hydrated minerals, key markers of past water and resources [1]. TES's olivine mapping [1] and CRISM's phyllosilicate detection in Mawrth Vallis [2] validate its Phase 1 role in pinpointing stable sites and water-bearing deposits for ISRU, such as habitat materials and ice extraction, over the 3-day mapping period.

2. Atmospheric and Climate Insights

In Phase 2, IR data tracks thermal emissions, dust storms, and water vapor, enhancing climate modeling with real-time monitoring akin to EMIRS [14]. This supports long-term atmospheric studies, informing habitat design and operational planning by predicting dust-related risks [13].

3. Human Exploration Support

IR-derived mineral maps complement UV-Vis data, providing a holistic resource and hazard dataset. It identifies dust-storm-prone regions and stable regolith, reducing EDL and equipment risks [17], and supports NASA's self-sustaining colony objectives by integrating with Artemis strategies [18].

VI. Conclusion

The M-STAR mission represents a pioneering application of distributed CubeSat technology to achieve comprehensive spectral analysis of Mars' surface and atmosphere, integrating ultraviolet-visible (UV-Vis, 200–700 nm) and infrared (IR, 0.7–10 μm) spectrometry across a constellation of 20 satellites. This mission, as outlined in the introduction, addresses the limitations of traditional single-orbiter spacecraft by enhancing data resolution, planetary coverage, and operational redundancy through a scalable, cost-effective framework. Deployed in a 175 km polar sun-synchronous orbit at an orbital velocity of 3.465 km/s, the network leverages proven instruments inspired by ALICE [3], TES [1], and CRISM [2] to conduct high-resolution mapping, as detailed in the mission overview.

In Phase 1, spanning three days, M-STAR completes a full spectral scan of Mars' 144.8 million km^2 surface using 25 km-wide swaths, enabled by the Chameleon SWIR camera system [5] for real-time dust and cloud tracking. The instrumentation design, featuring compact UV-Vis and IR spectrometers with adaptive optics and onboard calibration, ensures precise detection of organic molecules, volatiles, and minerals during this phase. Phase 2 extends the mission's utility over approximately five years, repurposing these systems for atmospheric monitoring, climate analysis, and communications relay, supporting future Mars missions with a robust lifespan based on CubeSat durability precedents [8], [9]. The data collection strategy, employing a variable duty cycle, real-time preprocessing, and efficient transmission via X-band or Ka-band to relay orbiters like the ExoMars Trace Gas Orbiter [6], sustains a daily downlink of ~500 MB, as described in the analysis section.

The scientific impact of M-STAR lies in its dual-wavelength approach, advancing planetary science by mapping surface composition (e.g., biosignatures, hydrated minerals) and atmospheric dynamics (e.g., dust storms, trace gases) with unprecedented coverage [2], [12]. For human exploration, it provides critical resource maps (e.g., water ice, silicates) and hazard assessments (e.g., dust-prone regions, radiation exposure), aligning with NASA's Artemis objectives [18]. By combining UV-Vis and IR data, M-STAR delivers a holistic dataset that enhances landing site selection, in-situ resource utilization (ISRU), and mission safety, supporting self-sustaining Martian colonies.

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VIII. Appendix

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# Appendix A: Mars Surface Scanning Time Calculation
# Purpose: Estimate time to scan Mars' surface with 20 CubeSats


# Constants
mars_surface_area = 144.8e6  # Total surface area of Mars (km²)
orbital_altitude = 175       # Altitude of CubeSats (km)
satellite_speed = 3.465      # Orbital velocity (km/s) at 175 km altitude
swath_width = 25             # Swath width per satellite (km)
num_satellites = 20          # Number of CubeSats


# Effective scanning rate per satellite (accounting for 50% swath overlap)
effective_swath_width = swath_width * 0.5  # Reduced due to overlap (km)
scanning_rate_per_sat = effective_swath_width * satellite_speed  # km²/s per satellite
total_scanning_rate = scanning_rate_per_sat * num_satellites  # km²/s for network


# Time to scan Mars' surface
time_seconds = mars_surface_area / total_scanning_rate  # Seconds
time_days = time_seconds / (24 * 3600)  # Convert to days
```

```
# Results
print("Mars Surface Area: {:.2f} million km²".format(mars_surface_area / 1e6))
print("Orbital Velocity: {:.3f} km/s".format(satellite_speed))
print("Effective Swath Width per Satellite: {:.1f} km".format(effective_swath_width))
print("Total Scanning Rate: {:.2f} km²/s".format(total_scanning_rate))
print("Time to Scan Mars: {:.2f} days".format(time_days))
```