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How did the technological advancements and mission objectives evolve across the Chandrayaan missions, and how did these changes influence India's lunar exploration outcomes?

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Abstract

This study investigates the evolution of technological capabilities and mission objectives across the three Chandrayaan missions – a defining phase in Indian lunar exploration. By comparing mission objectives and analysing ISRO's reports, this paper highlights the improvements in India's engineering capabilities and exploration agenda. The mission objectives progressed from orbital mapping and mineral detection to surface operations and soft-landing capabilities. While, the engineering capabilities advanced from basic orbital systems to complex landing architectures and autonomous control. These technological advancements directly contributed to India's improved international credibility and mission reliability in the space industry. The evolution also demonstrates India's adaptive engineering, rapid iterative designs, and emergence as a significant participant in global lunar exploration.

Keywords: Chandrayaan Missions, Lunar Exploration, ISRO, Technological Advancements, Mission Objectives, Space Technology, Soft Landing, Lunar Surface Exploration, Orbital Mapping, India's Space Programme.

INTRODUCTION

The Chandrayaan missions illustrate the evolution of India's lunar exploration strategy and engineering proficiency. Launched on 22 October 2008, Chandrayaan-1 marked India's first lunar probe. The probe orbited the moon at a height of 100km from the lunar surface to analyse the Moon's chemical composition and to determine the concentration and presence of minerals on the lunar surface. It was a scientific reconnaissance mission that focused on orbital exploration rather than surface operations. The orbiter integrated 11 scientific instruments, both international and Indian, in particular the Terrain Mapping Camera (TMC) for 3D mapping of the surface, Moon Mineralogy Mapper (M3) for detecting water molecules, and the Moon Impact Probe (MIP) designed to study and capture up-close images of the delicate lunar surface. The mission successfully established deep-space communication between Earth and lunar orbit, demonstrating India's capability in tracking, telemetry, and command operations beyond Earth's immediate orbital environment. It was the first Indian mission to successfully enter lunar orbit, marking a significant milestone in the development of India's engineering capabilities. Thus, Chandrayaan-1 laid the technological groundwork for India's transition from orbital reconnaissance to surface engagement. However, the mission's premature termination and lack of surface operation

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capability underlined the technological gaps that would later shape the objectives of Chandrayaan-2.

Chandrayaan-2 is an active Indian lunar mission launched on July 22, 2019. It is the second iteration of the Chandrayaan mission, aiming to widen the scientific findings of Chandrayaan-1. The mission targeted the lunar south polar region, and area of high scientific interest due to the possibility of water ice deposits. However, unlike Chandrayaan-1's Moon Impact Probe (MIP), Chandrayaan-2 planned to soft-land the Vikram lander for short duration surface experiments and deploy the Pragyan rover for in-situ elemental analysis of the lunar surface using laser-induced breakdown spectroscopy (LIBS). Furthermore, Chandrayaan-2 also aimed to investigate the impact of solar rays on the tenuous exosphere of the Moon. The Orbiter carried 8 scientific instruments, featuring a high-resolution camera and spectrometer for surface and exosphere studies. However, communication loss occurred during the final descent phase, which prevented successful soft landing. Despite the lander failure, the Orbiter remains operational, still to this date providing valuable scientific insights. Highlighting challenges in landing technology, autonomy and hazard detection. This outlined the framework for Chandrayaan-3 directly influencing the design and purpose.

The missions show a clear progression and enhancement in mission complexity from orbital studies to attempted successful landing to successful surface operations. The transition from primarily scientific reconnaissance to technology demonstration strengthened India's position in global space exploration.

Theory

Chandrayaan 3 India's third lunar exploration mission, was launched on 14 July 2023. The spacecraft consisted of three major components: a Propulsion Module, Vikram Lander, and Pragyan Rover. The Propulsion Module was the part of Chandrayaan-3 that carried the lander from Earth's orbit to lunar orbit. It was responsible for major course corrections and orientation of the craft around the moon. The Vikram Lander was the module designed to land safely on the Moon's surface. The lander is the aspect which controls the entire descent process from orbit to touchdown. It also deployed the Pragyan rover after landing. The Pragyan Rover was a small, six-wheeled robotic vehicle placed on the lunar surface to do in-situ elemental analysis and data collection. It conducted surface-level experiments and sent results back through the lander.

Chandrayaan-3 was designed to successfully demonstrate India's soft landing capabilities on the Moon and rover movement there, especially after the Chandrayaan-2 lander failure. The mission targeted the lunar south polar region, as an area of scientific interest to accumulate data related to predicted water ice deposits. Chandrayaan-3's engineering objective was to perform a precise, controlled descent and soft landing near the lunar south pole. Furthermore, to operate a rover (Pragyan) on the Moon's surface and move it safely over short distances as well as to establish reliable communication links between lands-rover-Earth. The mission's scientific objectives revolved around the study of the lunar surface's environment near the south pole in the following categories: measurement of how temperature changes with depth,

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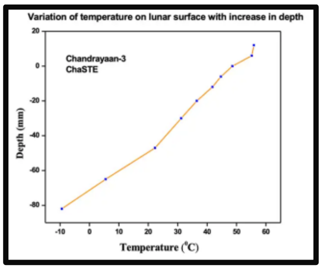
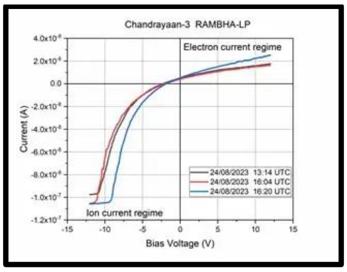
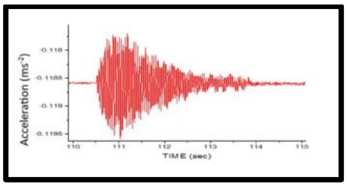
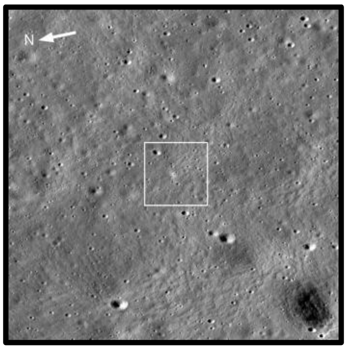
Moon's seismic activity, and the measure of plasma near the lunar surface. Moreover, the mission aimed to analyse the composition of the Moon's geological structure, specifically the identification of elements and minerals present due to its relevance for future human/robotic missions. Additionally, the mission hoped to make India a key contender in deep space exploration and space technology as well as to gain experience for future, more advanced missions.

Chandrayaan-3 carried a range of scientific instruments (payload) on its lander (Vikram), rover (Pragyan), and propulsion module to study the lunar south pole. The payloads include:

ChaSTE (Chandra's Surface Thermophysical Experiment) an instrument on the Vikram lander, which measures temperature variations in lunar soil up to 10 cm depth to understand heat conduction.	
RAMBHA-LP (Radio Anatomy of Moon Bound Hypersensitive Ionosphere and Atmosphere- Langmuir Probe) an instrument on the Vikram lander, which detects plasma density and temperature near the lunar surface.	
ILSA (Instrument for Lunar Seismic Activity) an instrument on the Vikram lander, which records seismic events (moonquakes) using a micro seismic sensor.	
LRA (NASA Laser Retroreflector Array) a passive experiment on the Vikram lander for precise distance measurement from Earth using laser ranging.	

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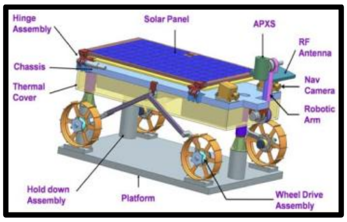
<td>APXS (Alpha Particle X-ray Spectrometer) a tool on the Pragyan Rover for analyzing elemental compositions of lunar soil and rocks via alpha particles and X-rays.</td>
<td>
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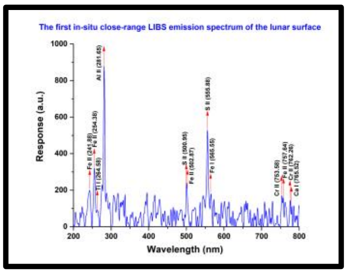
<td>LIBS (Laser Induced Breakdown Spectroscope) a instrument of the Pragyan Rover which determines the chemical composition of the Lunar surface by vaporizing soil with a laser and analyzing the plasma light.</td>
<td>
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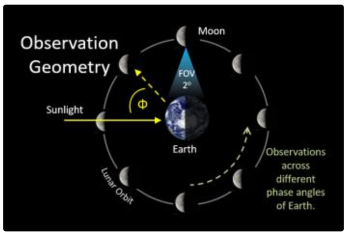
<td>SHAPE (Spectro-polarimetry of Habitable Planet Earth) an instrument for observing Earth for exoplanet studies, testing habitable planet detection techniques.</td>
<td>
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The mission resulted in India becoming the 4th ever country to achieve a soft landing on the moon, and the first-ever to land near the lunar south pole region. The mission demonstrated ISRO's safe landing capability, especially after the Chandrayaan-2 setback, it proved the strength of the guidance, navigation, and hazard detection systems. Furthermore, the Pragyan rover successfully transverse the lunar surface. The rover helped confirm the presence of sulfur, along with elements like aluminum, calcium, iron, chromium, titanium, manganese, oxygen, and silicon. The rover conducted a plethora of in-situ experiments including but not limited to: measuring of the surface temperature variations near the south pole, studying lunar seismic activity, and analyzing plasma density near the lunar surface. Moreover, the mission was completed at roughly ₹615 crore, proving highly cost-effective space engineering. Chandrayaan-3 boosted India's credibility in the space industry, and elevated ISRO's global standing.

From a future-oriented perspective, Chandrayaan-3 can be understood not merely as a standalone lunar mission, but as a critical preparatory phase in India's progression toward human spaceflight– specifically under the Gaganyaan program. While the mission itself did not involve crewed systems, its successful execution demonstrates a degree of technological advancement and operational dependability that is crucial for facilitating human missions in the imminent future. The validation of autonomous landing systems, precision navigation,

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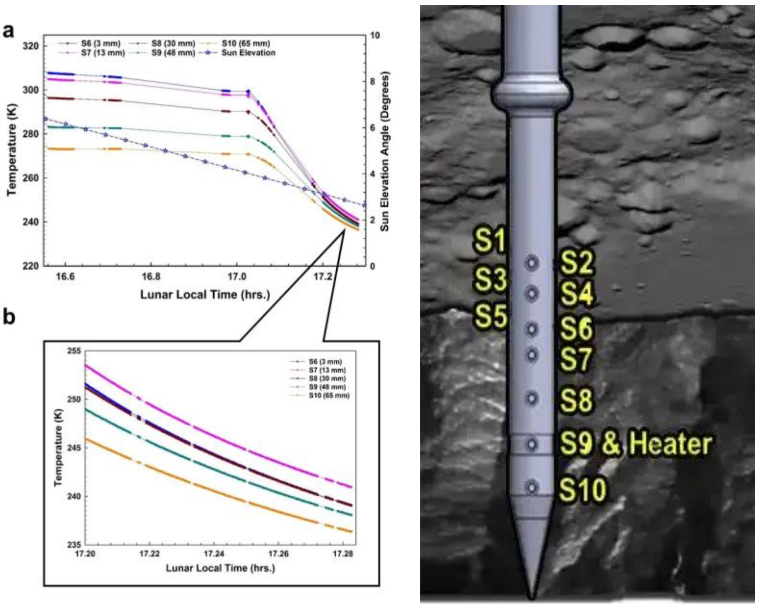
and real-time decision-making capabilities highlights the fact that ISRO's Chandrayaan-3 mission was the foundation to develop safe and crewed mission architectures. The ability to detect hazards, adjust trajectories autonomously, and maintain stable control under uncertain conditions contributes to the broader goal of minimizing risk in Gaganyaan missions, particularly during critical phases such as re-entry and recovery.

Experimental

The ChaSTE instrument onboard Chandrayaan-3 was used to measure the lunar soil at different depths near the Moon's south pole. The data shows that the surface of the Moon was much hotter compared to the deeper layers between it. The top layer recorded temperatures close to 330 Kelvin, while deeper layers dropped to around 268 Kelvin. This tells us that the Moon's surface absorbs heat quickly from the sunlight, but the heat does not travel easily into the lower layers. The significant decrease in temperature with depth suggests that lunar soil is a poor conductor of heat and acts like an insulator- trapping heat below its surface. The readings remained mostly stable during the observation period, reflecting a consistent thermal pattern.



The RAMBHA-LP instrument on Chandrayaan-3 made the first direct measurements of plasma near the Moon's south polar surface. The data was groundbreaking; it revealed that the Moon's electrical environment is much more active and dynamic than we previously presumed it to be. The electron density near the Shiv Shakti landing site (official name given to the Chandrayaan-3 lunar landing site) was measured between 380-600 electrons/cm^3, higher than earlier estimations. Electrons near the lunar surface were found to have very high energies, corresponding to temperatures of about 3,000-8,000 K. However, the lunar plasma

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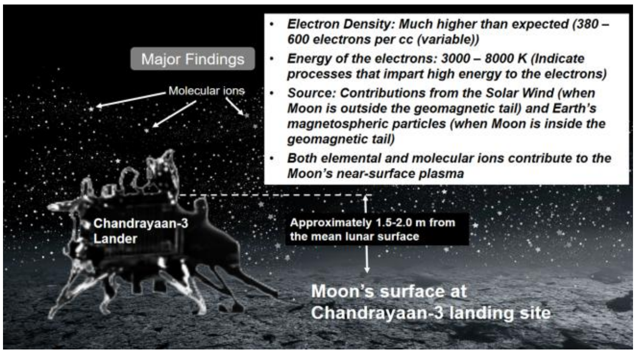
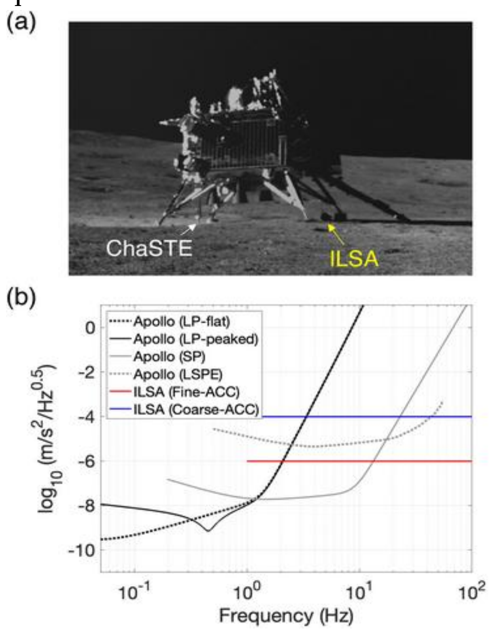
is continuously affected by solar wind particles and solar radiation. For instance, when the Moon passes through Earth's magnetotail, charged particles from Earth's magnetic field further alter the plasma environment. Additionally, results suggest that both elemental and molecular ions contribute to the formation of the lunar ionosphere.



The ILSA apparatus on Chandrayaan-3 consists of a set of six MEMS-based accelerometers deployed on the lunar surface. Three of the accelerometers were high-sensitivity sensors- they recorded fine acceleration data for detecting lunar vibrations and seismic data. Whereas, the other three accelerometers were lower-sensitivity sensors- they recorded coarse acceleration data to monitor lander tilt and stability. The instrument collected seismic data from 25 August to 4 September 2023, providing one of the first seismic datasets from the lunar south polar region. During this time period, ILSA recorded vibrations generated by rover activities, payload operations, and lander vibrations rather than naturally occurring moonquakes. The study identified characteristic vibration frequencies of the Chandrayaan-3 hardware; lander resonances near 5Hz and 10Hz, while rover resonances were close to 23-25 Hz and 40 Hz. These findings provided valuable information for the design of future lunar seismometers, showing they will need lower noise levels and longer operational lifetimes to reliably detect natural moonquakes.



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CONCLUSION

In conclusion, the Chandrayaan missions demonstrate a clear evolution in India's exploration strategy, progressing from orbital observations, all the way to surface explorations and successful lunar operations. Each mission contributed important technological lessons that allowed the development of more advanced systems, particularly in navigation, communication, landing autonomy, and scientific instrumentation. Chandrayaan-3 represents a major milestone in Indian space exploration because it successfully validated technologies that previous missions were unable to fully achieve, most importantly a controlled soft landing and rover deployments. The scientific payloads in the mission provided valuable insights into the lunar south pole, an area that remains largely unexplored by other missions. Thereby, contributing new knowledge to the global scientific community, making India a recognised contender in the space industry. A key strength of the Chandrayaan program is ISRO's ability to achieve significant scientific and engineering marvels through cost-effective designing and the iterative models of the missions. Despite its success, the mission was limited by a relatively short operational period, restricting the amount of long-term environmental data that could be collected. However, some observations- particularly seismic measurements, were affected by instrument noise and operational disturbances, highlighting challenges that future missions must address. The findings of this study suggest that future lunar missions should focus on longer-duration surface operations, improved seismic instrumentation with specific frequency fine-tuning, and expanded in-situ investigations of the lunar south pole. Overall, the evolution of the Chandrayaan missions reflects India's growing capability in deep-space exploration and establishes a strong technological foundation for future lunar exploration initiatives and human spaceflight programs such as the Gaganyaan mission.

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