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PERMACULTURE BACK TO NATURE

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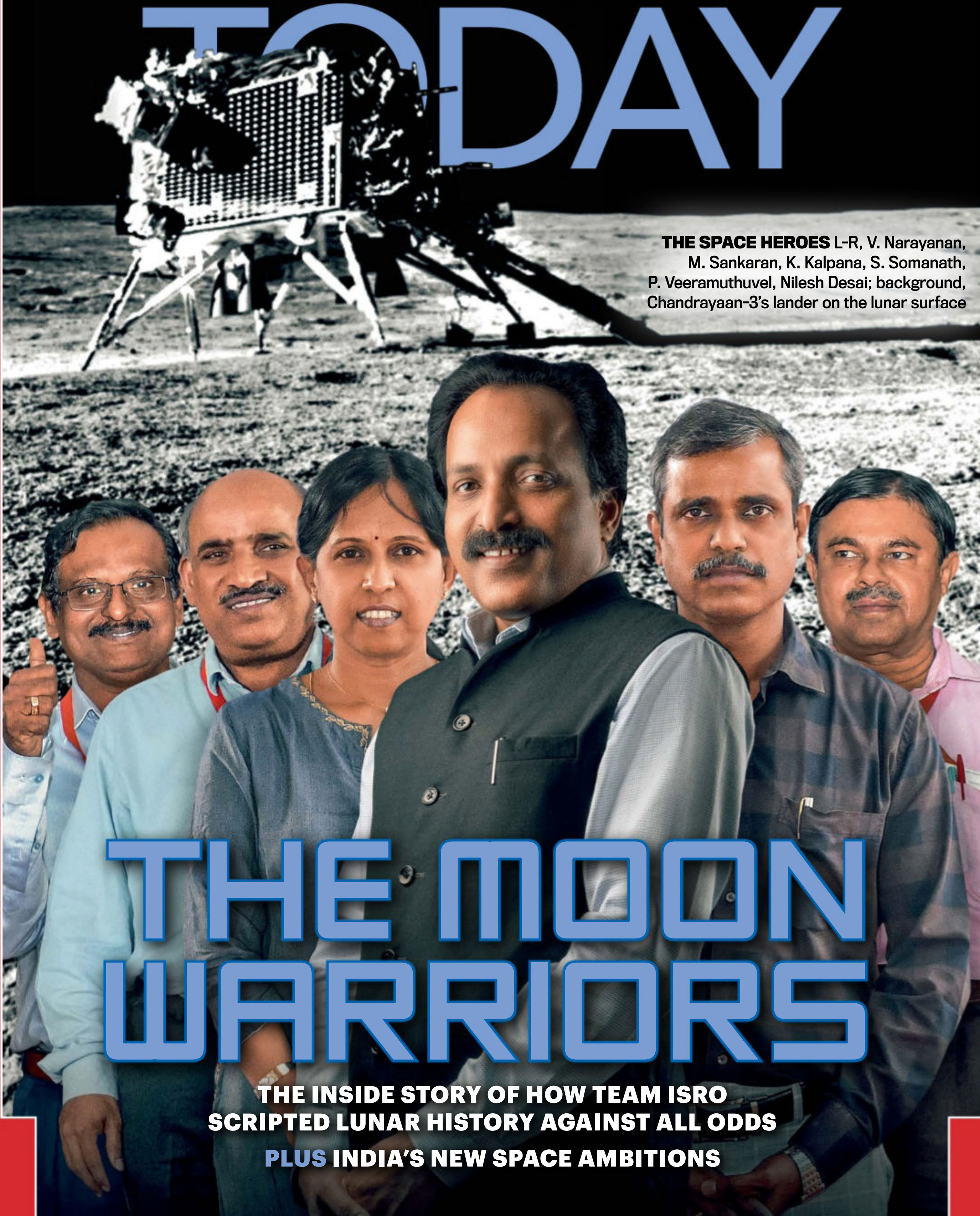

THE SPACE HEROES L-R, V. Narayanan, M. Sankaran, K. Kalpana, S. Somanath, P. Veeramuthuvel, Nilesh Desai; background, Chandrayaan-3's lander on the lunar surface

THE MOON WARRIORS

THE INSIDE STORY OF HOW TEAM ISRO SCRIPTED LUNAR HISTORY AGAINST ALL ODDS

PLUS INDIA'S NEW SPACE AMBITIONS

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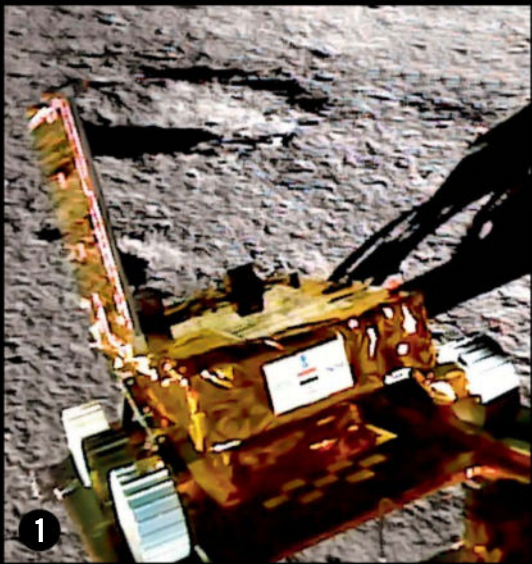

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2

THE MOON

THE MEN AND WOMEN WHO MADE INDIA'S LUNAR ACCOMPLISHMENT
AND NEVER-SAY-DIE ATTITUDE. THEY ARE A BRILLIANT EXAMPLE OF HOW

Photographs Courtesy: ISRO

MOONSTRUCK

1. A video grab showing the Pragyan rover descending the ramp to the lunar surface

2. A picture of the Vikram lander clicked by the navigation camera on Pragyan rover

3. Pragyan rover roaming around the Shiv Shakti point

4. PM Modi with ISRO scientists

WARRIORS

POSSIBLE BY THE SHEER DINT OF THEIR DEDICATION, HARD WORK TO SCRIPT SUCCESS OUT OF FAILURE

BY RAJ CHENGAPPA

MOX or Mission Operations Complex-2 in the heart of Peenya, a teeming hub of small-scale industries in Bengaluru, has an unimpressive PWD-type façade. The road leading up to it does have a fresh coat of tar. It was in preparation for Prime Minister Narendra Modi's visit on August 26 to congratulate Indian Space Research Organisation (ISRO) scientists for the superlative success of the Chandrayaan-3 mission to the moon. But it had to be put off till after his visit due to security reasons.

On the MOX porch are displayed real-size models of Vikram, India's now-famous moon lander, and its companion, the Pragyan rover. They were transported from the UR Rao Satellite Centre (URSC) at the other end of the city for the PM's benefit. Sheathed in a shiny gold-coloured thermal blanket, Vikram, with its four landing legs, is surprisingly tall—around 10 feet—but has a squat box-like appearance. Weighing 1,742 kilograms, landing it on the moon is like dropping a mini-SUV on the satellite's surface. Pragyan, the rover whose glistening aluminium wheels bear the imprint of India's national emblem, resembles an oversized skateboard. ISRO scientists and their families were busy taking selfies with the spacecraft replica before it was dismantled and returned to the URSC.

Inside MOX-2, the three mission control halls were a hive of activity when INDIA TODAY visited their premises on August 29. The Chandrayaan project team had to move to another set of computer consoles to make way for the Aditya L1 mission team that was preparing for the spacecraft's launch on September 2 to study the sun. That's just how busy ISRO is these days. On the high walls of the complex were giant computer screens that displayed

WITH CHANDRAYAAN-3, ISRO CHOSE A FAILURE-BASED APPROACH AND CLEARANCE FROM ALL TEAM HEADS BEFORE LAUNCH

dashboards of Vikram's health and Pragyan's movements. The rover literally crawls over the grey-black scarred lunar surface at a 'top speed' of one centimetre per second, with two front-loaded cameras acting as its eyes. The terrain is hazardous, full of deep craters; on that day, the rover had to reverse from one just eight metres away from the lander. But not before swivelling around and taking the very first photograph of Vikram on the lunar surface, an image destined to become a permanent symbol of India's prowess.

Back on Earth, hunched on one of the consoles is the unassuming 46-year-old Palanivel Veeramuthuvel, in a dark cotton long-sleeved shirt and fawn-coloured check pants, his salt-and-pepper hair combed neatly back. A native of Tamil Nadu, Veeramuthuvel studied in the Villupuram railway school before completing an engineer-

MOON-WALKERS

1. The launch of Chandrayaan-3 on July 14

2. ISRO control room during Chandrayaan-3 landing on Aug. 23

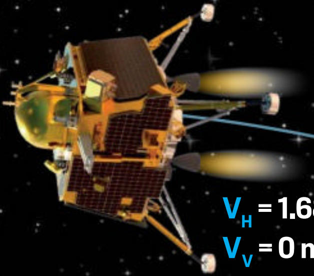
3. ISRO chairman S. Somanath with the women scientists involved in the Chandrayaan-3 mission at ISTRAC

ing degree from a Chennai college and an M.Tech. from an institute in Tiruchirappalli. A brief stint in HAL preceded his shift to ISRO in 2004, which he joined because it had a "huge brand name". Now, as project director for Chandrayaan-3 for the past four years, on his slender shoulders lay the enormous weight of meeting the nation's space expectations and ensuring that the ISRO brand remained untarnished. As also the prestige of hundreds of Indian space scientists and engineers who have worked tirelessly to make the moon mission a success. Speaking softly but firmly, Veeramuthuvel describes himself as a "simple person" who believes that "self-discipline, 100 per cent involvement without any expectation and hard work never go unrewarded".

Not always, though. Four years ago, on September 6, 2019, he and hundreds of other scientists had to watch the Chandrayaan-2 lander spin out of control 800 metres above the lunar surface and then lose all telemetry contact with mission control as it crashed on the moon. It would fall on then ISRO chairman P. Sivan to break the gloomy news to PM Modi, who was in the visitors' gallery to watch the landing and who had to console Sivan in turn, as pent-up emotion got the better of him. Among those present at mission control that day was S. Somanath, who was then the director of the Thiruvananthapuram-based Vikram Sarabhai Space Centre (VSSC). As he recalls, "We were all sad because we had seen its wonderful performance before that and towards the end we really had no confirmation of whether it had landed safely or crashed because there was no data coming to confirm either way due to the communication failure."

Four years later, the tall, fit and unflappable Somanath

30 km



V_H = 1.68 km/ sec
V_V = 0 m/ sec

V_H = Horizontal velocity
V_V = Vertical velocity

V_H = 358 m/sec
V_V = -61 m/sec

V_H = 336 m/sec
V_V = -59 m/sec

7.4 km

6.8 km

TAKE-NO-CHANCES APPROACH

Big changes between Chandrayaan-2 and 3

NAVIGATION

Multiple sensors and instruments to check altitude, velocity and descent to log accurate, real-time data on the descent path. These included:

- **Altimeters**: To measure altitude variations, upgraded laser and radio frequency-based altimeters used
- **Velocimeters**: To gauge velocity, there was an all-new laser Doppler velocimeter apart from an improved lander horizontal velocity camera
- **Inertial system**: For flight path, there was improved laser gyro-based inertial referencing and accelerometer package
- Improved lander hazard detection and avoidance camera to ensure landing at suitable spot

PROPULSION SYSTEM

- Four instead of five 800N throttleable liquid engines
- Slosh mitigating by anti-slosh baffle in the propellant tanks
- Rigorous integrated testing of engines, valves, and electronics for better performance
- 182 kg more fuel carried to give greater manoeuvrability

GUIDANCE CONTROL SYSTEMS

- Improved software designed for powered descent trajectory
- Multiple mission paths built for soft-landing for contingencies
- Thrust and angle continuity throughout the descent by appropriate selection of guidance algorithm
- Instantaneous thrust corrections: Done for deviations unlike in Chandrayaan-2

ALTITUDE

800/ 1,300 m

150 m

60 m

ROUGH BRAKING PHASE
(690 sec)

ATTITUDE HOLD PHASE
(10 sec)

0 km

713.5 km

3.48 km

745.5 km

DOWNRANGE TRAVELLED

32 km

28.52 km

LUNAR EXPERIMENTS

BY LANDER

- Radio Anatomy of Moon Bound Hyper-sensitive Ionosphere and Atmosphere: To measure the near surface plasma (ions and electrons) density and its changes with time
- Chandra's Surface Thermophysical Experiment: To measure the thermal properties of the lunar surface
- Instrument for Lunar Seismic Activity: To measure seismicity around the landing site and delineating the structure of the lunar crust and mantle
- Laser Retroreflector Array: To understand the dynamics of the moon system

BY ROVER

- Laser-induced Breakdown Spectroscope: To derive the chemical composition and infer mineralogical composition of lunar surface
- Alpha Particle X-ray Spectrometer: To determine the elemental composition, including magnesium, aluminium, silicon, ferrous and other minerals of lunar soil and rocks, around the landing site

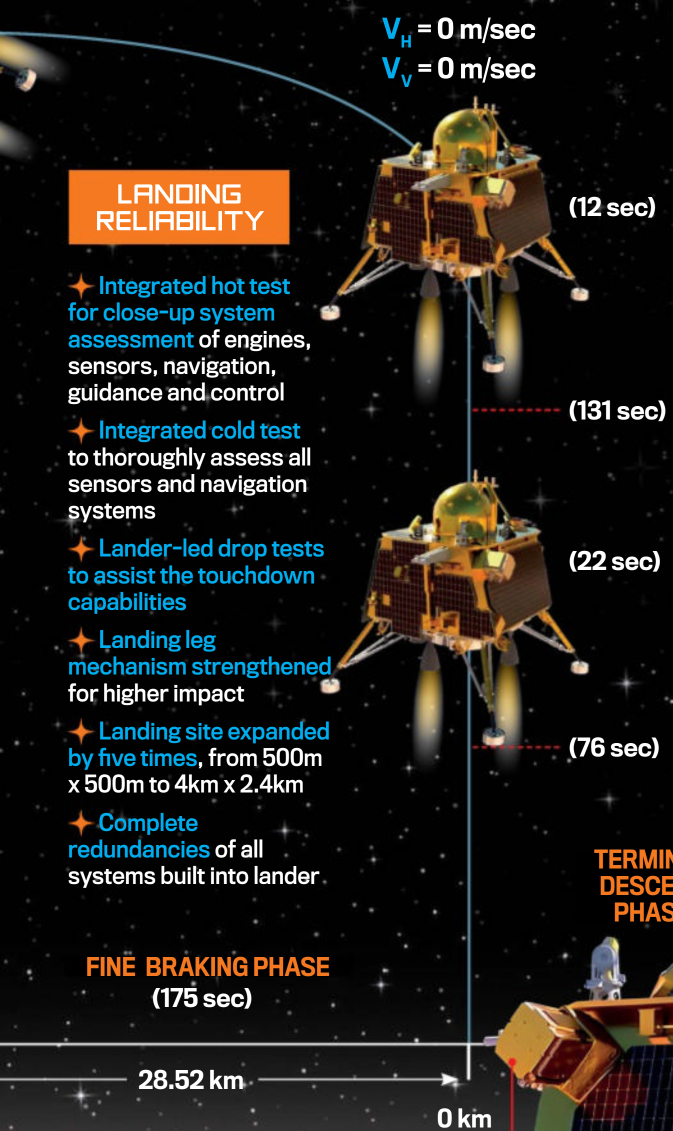
FROM FAILURE TO SUCCESS

How the lessons learnt from the 2019 Chandrayaan-2 disaster contributed to the success of India's third lunar exploration mission

Graphic by NILANJAN DAS *and* TANMOY CHAKRABORTY

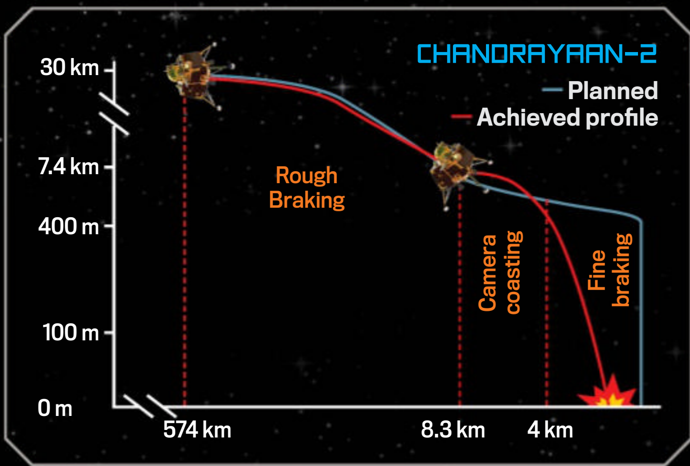
CHANDRAYAAN-3: MISSION OBJECTIVES

- To demonstrate safe and soft landing on lunar surface–*Done*
- To demonstrate rover traversing the moon–*Done*
- To conduct in-situ scientific experiments –*In progress*



LANDING RELIABILITY

- Integrated hot test for close-up system assessment of engines, sensors, navigation, guidance and control
- Integrated cold test to thoroughly assess all sensors and navigation systems
- Lander-led drop tests to assist the touchdown capabilities
- Landing leg mechanism strengthened for higher impact
- Landing site expanded by five times, from 500m x 500m to 4km x 2.4km
- Complete redundancies of all systems built into lander



THE PRAGYAN

(Sanskrit for 'wisdom')

Size
Chassis: Length 91.7 (3.05 ft); breadth 75.0 (2.5 ft); x height (1.32 ft)

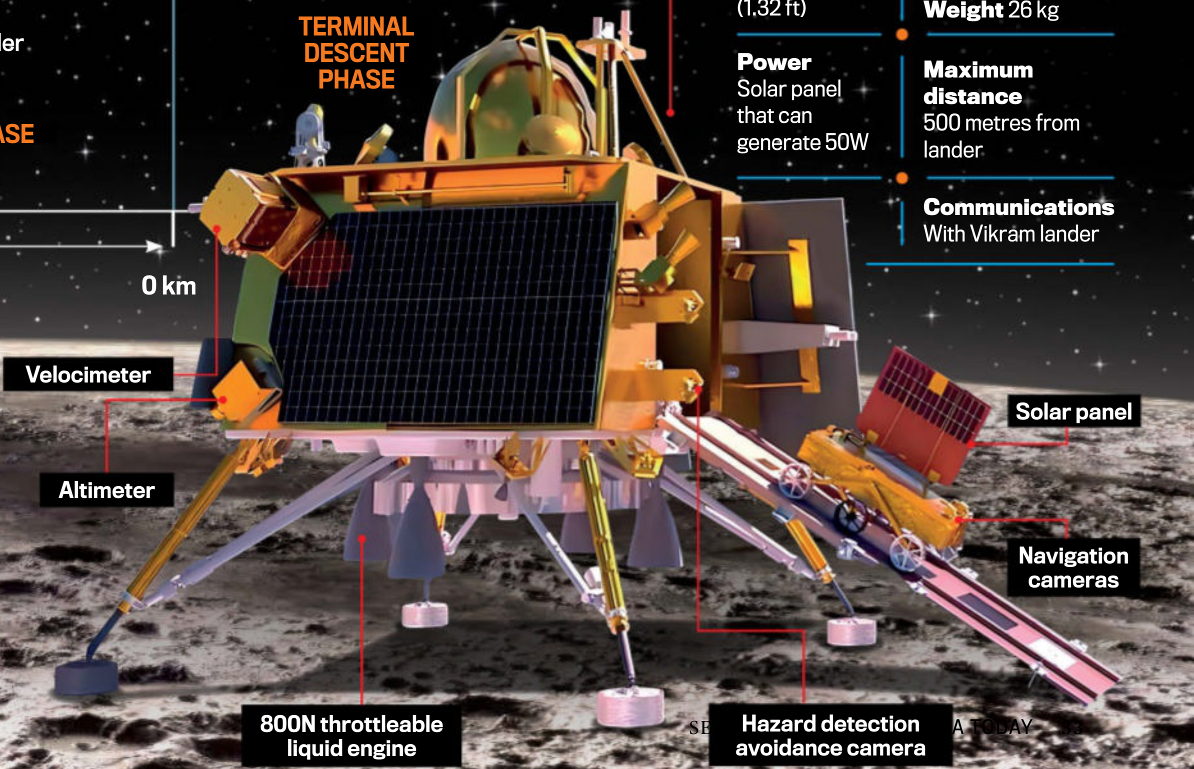
Movement
Six-wheel rocker-bogie wheel drive assembly

Weight 26 kg

Power
Solar panel that can generate 50W

Maximum distance
500 metres from lander

Communications
With Vikram lander



would once again find himself sitting in front of a console at MOX-2—though this time as ISRO chairman—as the countdown began for the final descent of the Chandrayaan-3 lander. Next to him, Nilesh Desai, director of the Space Applications Centre (SAC) in Ahmedabad, was conscious of the recent failure of Russia's Luna 25, which too was to land near the South Pole and worried about the "unknown unknowns", as Sivan called them. Somanath himself was unusually calm. Having seen 50 rocket launches since he joined ISRO in 1985, the sexagenarian says, "I do not have the habit of getting excited. We had done all that we could to ensure success. There was nothing more we could do and I remained confident." That supreme confidence—his own as well as the team's—came from the hard work they had put in to correct the flaws of the previous launch and prepare for any exigency, including the unknown unknowns.

This, then, is the inspirational story of how Team ISRO pulled itself from the depths of despair, against all odds, to script lunar history. Together, they would make India only the fourth country to land a spacecraft on the moon and the first to do so near the unchartered and treacherous South Pole.

THE DEPTH OF DESPAIR

Four years ago, when ISRO lost contact with Chandrayaan-2 during its descent to the lunar surface, it would take days to locate the fallen lander. Only after a photograph taken by its lunar orbiter, which, unlike the lander, happened to be doing its job perfectly, did scientists get to know that it had crash-landed and lay sprawled on the lunar surface. As per protocol, Sivan, as ISRO chairman, formed a national failure analysis committee (FAC), headed by the experienced and accomplished V. Narayanan, director of the Liquid Propulsion Systems Centre (LPSC) in Thiruvananthapuram. Narayanan's team had put together the propulsion system for Chandrayaan-2, and its failure had left him stunned and disappointed. He was given a month to look into the entire performance of Chandrayaan-2 and its systems, pinpoint the reasons for the setback and make recommendations for a successful landing the next time. At the end of the month, the team came out with a 900-page report on what went wrong and how to overcome those problems.

Unforgiving as space is, a deviation of even one per cent or a faulty system can end in catastrophic failure. That is what the committee discovered when it examined the reasons for Chandrayaan-2's failure. Sivan, who was still chairman, recalls, "There were issues with all the three major systems critical to the spacecraft—propulsion, navigation and guidance control."

SPACE'S ELEVEN

The key individuals behind one of the most spectacular space missions undertaken by India

S. SOMANATH, 60

Chairman, ISRO

ISRO's 'Captain Cool', Somanath joined the Vikram Sarabhai Space Centre in 1985 and later contributed to the development of the PSLV and the giant GSLV Mark III. Before becoming ISRO chairman in 2022, he had overseen the propulsion systems for the Chandrayaan-2 lander. Somanath studied mechanical engineering at Kollam's TKM College and has a Master's degree in aerospace engineering from IISc.

P. VEERAMUTHUVEL, 46

Project Director, Chandrayaan-3

Born in Tamil Nadu's Villupuram district, Veeramuthuvel has been part of some of India's toughest space missions, including the Mars Orbiter. He did an engineering degree from Chennai, then an M.Tech., and after a brief stint with HAL, joined ISRO in 2004 as a project engineer. Simultaneously, he completed his Ph.D. from IIT Madras. As project director for Chandrayaan-3, he oversaw coordination between key ISRO centres.

M. SANKARAN, 59

Director, UR Rao Satellite Centre, Bengaluru

As director of the lead centre for the design and development of ISRO satellites, Sankaran played a key role in developing the communication and power systems for the Chandrayaan and Mars Orbiter missions. He joined the URSC after obtaining a Master's degree in Physics in 1986 from the Bharathidasan University, Tiruchirappalli. He is now spearheading the avionics design, electronics and power systems of the Gaganyaan programme.

S. UNNIKRISHNAN NAIR, 59

Director, Vikram Sarabhai Space Centre, Thiruvananthapuram

An expert in launch vehicle designs, Nair led the team that ensured ISRO's heavy lift launcher LVM3 put Chandrayaan-3 into the desired orbit. As founding director of the Human Space Flight Centre, he is playing a key role in the Gaganyaan project now. An alumnus of IISc and IIT Madras, Nair joined VSSC in 1985 and took over as director in 2022. He has also published short Malayalam stories.

NILESH M. DESAI, 59

Director, Space Applications Centre, Ahmedabad

Desai took charge of the SAC in 2021. ISRO's lead centre for the "design and development of space-borne instruments", SAC provided the Chandrayaan-3 lander imager cameras, Ka-band altimeter, hazard avoidance sensors and rover imagers along with their data processors. Desai is an engineering gold medallist from an Ahmedabad engineering university. He joined SAC straight out of college and became a specialist in microwave and radar systems.

B.N. RAMAKRISHNA, 58

Director, Telemetry, Tracking and Command Network Centre (ISTRAC), Bengaluru

ISRO's control centre for deep space missions, ISTRAC, headed by Ramakrishna, is the key communication link to all of ISRO's orbiting spacecraft, including the Chandrayaan. Ramakrishna has an M.Sc. and is an expert in orbit determination of spacecraft.

K. KALPANA, 49

Associate Project Director, Chandrayaan-3

Kalpana had dreamt of working with ISRO since childhood. After obtaining an engineering degree from a college in Chennai, she joined the space agency in 1999 as a radar engineer. She assisted Veeramuthuvel in the Chandrayaan-3 project and was closely associated with the Mangalyaan missions too.

V. NARAYANAN, 59

Director, Liquid Propulsion Systems Centre, Thiruvananthapuram

The LPSC, led by Narayanan, delivered the propulsion systems for the Vikram lander, including the thrusters for soft landing. A cryogenic engineering expert, he had chaired the panel that studied the crash of Chandrayaan-2's lander and recommended changes. Narayanan was born in Tamil Nadu, in Kanyakumari's Melakattuvilai village, to a farmer father. He has an engineering degree from the Govt. Polytechnic College, Nagercoil, and an M. Tech. and a Ph.D. in aerospace engineering from IIT Kharagpur.

ANIL BHARDWAJ, 56

Director, Physical Research Laboratory, Ahmedabad

A Ph.D.-holder in applied physics from IIT BHU, Bhardwaj headed the Space Physics Laboratory at VSSC before taking up his current post at PRL. He is a recipient of numerous awards, including the Bhatnagar Prize for scientists (2007) and the Infosys Prize (2016). The Chandrayaan-3 lander Vikram and its rover Pragyan, used to study the moon's surface, were developed by the PRL under his guidance.

M. SRIKANTH, 45

Mission Operations Director, Chandrayaan-3

M. Srikanth has been with ISRO for two decades. Hailing from Thiruvananthapuram, the B.Tech. graduate contributed to the Chandrayaan-1 and 2 missions. For Chandrayaan-3, he spearheaded the navigation aspect and was part of the planning and safety protocols.

S. MOHANA KUMAR, 59

Mission Director, LVM-3

It was S. Mohana Kumar, Chandrayaan-3's mission director, who first announced its successful launch on July 14 from the Satish Dhawan Space Centre in Sriharikota, saying, "This is the result of the penance of many across ISRO centres." Kumar, who has been with ISRO for 30 years now, played a major role in the launch vehicles for Chandrayaan spacecraft and also led the launch of Oneweb India 2 satellites in March this year.

All these took place in what Sivan had famously described as "15 minutes of terror", the time taken for the lunar craft to break out of its orbit around the moon and land on the surface, a phase that is completely autonomous. Everything seemed to have been going fine with Chandrayaan-2 in what is known as the rough braking phase of the craft's descent. At the start of this descent, 30 km above the lunar surface, the spacecraft was going at 6,000 kmph, 3x the maximum speed of IAF's top-of-the-line jet fighter the Sukhoi Su30MKI. That speed had to be brought down to around 1,200 kmph (400 kmph more than a passenger jet's average speed of 800 kmph) and its height to around 8 km above the lunar surface. To do so, the spacecraft had to retrofire four of its engines to act as a braking mechanism and simultaneously command its cluster of eight thrusters to tilt the spacecraft at the angle needed for descent mode.

On the consoles, the spacecraft seemed to be doing exactly as it was meant to in this phase. In the next phase, known as the camera coasting or attitude hold phase, the spacecraft evaluates its position and decides if it needs course correction for the fine braking phase. Unknown to the mission team, things had started going wrong because the four thrusters over-delivered, reducing the spacecraft's speed by an additional 100 kmph. The navigation and guidance systems meant to compensate for the reduction in speed started an aggressive manoeuvre to steer it back on course. However, serious software errors began to occur at this point, confusing the spacecraft and even making it do an unplanned somersault. Meanwhile, instead of the engine thrust getting lowered, it was boosted to the maximum as the spacecraft's autonomous guidance and control systems desperately tried to correct the anomalies. By then, it was already too late, and the lander rammed into the moon's surface at a speed of 180 kmph, overshooting the designated spot by 500 metres. As a senior ISRO scientist puts it, "Instead of a normal 3-Sigma dispersion that the craft could have taken care of, we were dropping to sigma levels way beyond the capacity of the control systems to handle major deviations."

THE FIGHTBACK

It is to the credit of the ISRO failure review system that it successfully pinpointed the root cause of the problems without allowing any acrimony to develop between the various teams. Clearly, every major system at the landing stage was accountable for the errors reaching unmanageable proportions, necessitating a complete overhaul of the spacecraft. In what was a saving grace for Team ISRO, Chandrayaan-2's orbiter was performing optimally, sending continuous data about the moon's surface and contributing immensely to Chandrayaan-3's success.

WHILE INVESTIGATING CHANDRAYAAN-2'S FAILURE, PROBLEMS WERE FOUND WITH ITS PROPULSION, NAVIGATION AND GUIDANCE CONTROL

Knowing what caused Chandrayaan-2's failure was only half the battle won. The tougher part was overcoming the mistakes. Veeramuthuvel, who was associate project director of Chandrayaan-2 and had gained immense understanding of the systemic issues involved, was made project director for Chandrayaan-3 in December that year. Kalahasti Kalpana, 49, who too had worked on Chandrayaan-2, was made his associate project director. Kalpana, who graduated from a Chennai engineering college, had joined ISRO as a radar engineer in 1999. Her experience reflects the ISRO culture of fostering gender equality, and Kalpana says, "I have never felt we are not equal, or discriminated against, because of my gender at ISRO. In all discussions and tasks, we are treated on par with men."

TRIAL RUN
The Vikram lander during an electromagnetic interference/compatibility test at the UR Rao Satellite Centre, Bengaluru

Covid played spoiler for almost a year, seriously disrupting the work on correcting Chandrayaan-2's errors. Top-level changes also began happening. For one, Muthusamy Sankaran took over as director of URSC—the nodal centre that is responsible for the integration of the spacecraft, including for Chandrayaan-3—in June 2021. The clear-thinking Sankaran, 59, who had worked both on the Chandrayaan and the Mangalyaan (Mars) projects, concluded that the chief learning from the failed effort was that the lander was more than just a spacecraft. It was also a satellite with a reusable rocket and an aircraft with a sense of awareness of how and where to land. "It's really a three-in-one craft," explains Sankaran, "and once we treated it in this holistic way, we began to have a better understanding of how to make it work successfully." He also realised that the telemetry data from the crashed lander was limited and would not provide any major clue to what went wrong. He, therefore, pushed for recreating what happened in the final minutes of the craft's descent and then came up with robust solutions to correct it.

Somanath succeeded Sivan as ISRO chairman in January 2022. In addition to a cool-headed approach, Somanath combined his dynamism with a derring-do attitude that enthused the members of his team. He also brought to the table the vast experience of designing and handling complex missions, including the previous Chandrayaan ones. Somanath introduced two major changes in the management style of the project. The first, he termed a failure-oriented approach, a variation of the old Murphy's Law according to which everything that can go wrong will go wrong. He clarified that such an approach did not come from a place of pessimism, it was rather a departure from the assumption of success and hope of all going well, and instead mapping all that could go wrong to then work out how to eliminate glitches or introduce backup systems.

The second was, as he told his team, "We will not go for the launch of Chandrayaan-3 unless there is 100 per cent satisfaction of all the teams involved." That mandate saw every aspect of the lander and rover being stripped threadbare all over again and tested. From descent to touchdown, there are 170 such critical parameters, each of which was tested and retested till each team involved built enormous confidence levels. Veeramuthuvel recounts with a smile that when he reported to Somanath he was confident that the problem had been sorted, he told him, "It is not for you to say that you are confident. The team handling it should be saying it." Somanath also tapped into the vast pool of retired ISRO scientists to review the process and guide the teams. Prominent among them was former ISRO chairman A.S. Kiran Kumar, who provided invaluable insights into the modifications needed for success.

TAKE-NO-CHANCES APPROACH

Each of the key systems teams then got down to identifying and correcting the errors and in the process introduced more than 20 major changes across the board after the Chandrayaan-2 experience. In the propulsion systems, for instance, it examined in depth what could have caused the four engines to overperform in the rough braking phase. To do so, LPSC's Narayanan had his team strap the four engines on a platform at his centre at the Valiamala complex in Thiruvananthapuram and fire them for the entire duration of Vikram's planned descent. It was here that the team detected a missing electronic pulse that controls the valves regulating the flow of propellants. It had resulted in a small excess that caused the engines to overperform. This was corrected by ensuring that the fuel flow was a little more sluggish to compensate for any errors. Then, the four engines were strapped on to a Vikram platform that had all the vital systems such as sensors and control systems and hung on a 60-metre-tall tower at the Sriharikota launchpad. These were fired to see if the vibrations caused by the rocket engines were disturbing the sensors and to prevent the sloshing of fuel impacting the spacecraft's centre of gravity while in flight. Those issues were sorted by bolstering them with dampeners.

When it came to the guidance and control systems, which constituted the brains of Vikram, since the entire process was autonomous, all the 116,000 software lines, as these were called, were reviewed and improvements made in addition to widening the dispersion and deviations that it could handle. Somanath even had a separate team from VSSC that was not involved with the software systems to independently check all parameters and ensure that all the bugs were fixed. Then to see if the guidance control systems worked, Veeramuthuvel had the team hire a helicopter and fly a model of the Vikram. It hovered over the ground at a height of 150 metres, the same at which it would on the moon. To avoid the control issues of

Chandrayaan-2, errors were programmed to get sorted as and when they arose and not wait for the coasting phase.

Meanwhile, at the SAC in Ahmedabad, Desai had all the 11 sensors that monitor the major parameters of Vikram and the eight cameras that act as its eyes tested rigorously and ruggedised. This included vast improvements in the Lander Hazard Detection and Avoidance Camera (LHDAC) that kicks into action in the final minutes of Vikram's descent. The craft hovers over the landing spot at a height of 150 metres and waits till the pictures from the LHDAC confirm that there are no boulders, craters or other obstacles before descending further. Redundancies were also built into the cameras to ensure that if one fails, the other would assume its place. They even simulated the lunar surface by transporting sand from Salem similar to lunar regolith and created a mini landing strip complete with craters and boulders to test the cameras.

There were other innovative solutions. With the Chandrayaan-2 lunar orbiter a success, the team dispensed with the need to have a long-duration orbiter for Chandrayaan-3. So its orbiter was made lighter and the lander heavier by over 250 kg. This allowed them to fix more back-up instruments to build redundancy in the event that any failed. Much of this capacity was used to carry extra fuel to meet any exigencies and deviations on the planned descent path. On the previous occasion, there was just a "touch-and-go" amount of fuel, which cramped the autonomous decision-making process. Now, they could carry an extra 182 kg of fuel. With the Vikram lander getting heavier, the fifth engine in the Chandrayaan-2 lander for use in its final descent phase was also dispensed with. The current lander, therefore, has four engines, two of which kept firing till touchdown. The removal of the fifth engine from the lander's belly made its centre of gravity more stable while also raising the ground clearance, which was essential if the craft encountered undulating terrain. Vikram's leg pads, too, were strengthened to absorb twice the force if needed. These leg pads are made of aluminium in a unique honeycomb pattern that gets crushed on impact, absorbing most of the shock of the fall.

WITH AN ORBITER ALREADY IN PLACE, IT WAS DISPENSED WITH, MAKING THE LANDER LIGHTER. A FIFTH ENGINE TOO WAS REMOVED

Another issue was related to the area that had been identified for Chandrayaan-2's landing. It was a narrow band of 500 metres by 500 metres, which made manoeuvring even more complex. To circumvent this problem, the Chandrayaan team used its existing orbiter to map the landing region thoroughly and expanded the landing zone to 4 km by 2.4 km. As a team member put it, "The comparative difference is like landing on a football field instead of a tennis court."

All the niggles thus sorted and every head of systems involved in Chandrayaan saying they were satisfied that they had made failsafe improvements, Somanath gave the clearance to launch the spacecraft on July 14, 2023. After the LVM3 launched the Chandrayaan-3 propulsion module and lander perfectly into orbit, Mohana Kumar, the mission director, said, "This successful launch is the result of the penance of many ISRO centres across the country." Indeed it was.

Veeramuthuvel, who was at the launch pad, knew it was now over to him and his team to prove its success. He had worked hard for it and become so passionately involved that URSC's Sankaran would joke, "We were worried that he would strap himself to LVM3 and personally escort Vikram to the moon." It would take 40 days before the team would attempt to land Vikram after it successfully detached from its module. On D-Day, both Veeramuthuvel and Kalpana were huddled over their consoles. "The first thing we watched for," says Kalpana, "was the rough brake phase, which went beautifully. Our hearts beat faster as we approached the phase where it had failed the last time." Once Vikram crossed that rubicon, Veeramuthuvel would look at Kalpana and smile. "Once that went through," he says, "we were confident that it would land perfectly. Thousands of people had worked on the mission and had done everything that was humanly possible to ensure there was no failure."

Not far from them sat Somanath with other top ISRO team members keeping a close watch on the console. When Somanath saw the five green squares flash on his console, which indicated that Vikram had accomplished a soft landing on the moon and all systems were functioning fine, he would shake hands with his colleagues, walk across to Veeramuthuvel and hug him. After that, he went on the dais to inform the prime minister, who was watching the event live on a television screen in Johannesburg, where he had gone for a BRICS meeting. As Modi happily waved the Indian flag, Somanath told him, "Honourable Prime Minister, we have achieved soft landing on the moon. India is on the moon." It was, if one were to rephrase what Neil Armstrong said in 1969, another small step for humanity, but a giant leap for India. ■

EXCLUSIVE INTERVIEW

"FAILURES GIVE YOU MUCH MORE UNDERSTANDING THAN SUCCESS"

The man of the moment, *ISRO chairman* DR S. SOMANATH, spoke at length to *Group Editorial Director* RAJ CHENGAPPA on the outcome of India's moon missions and beyond. Edited excerpts from the interview

Photograph by BANDEEP SINGH

Q. What do you see as the main achievements of Chandrayaan-3?

There are many. With a mission strategy to reach the moon at a comparatively slow pace and accomplish a soft landing while ensuring minimal cost is a very unique management plan that is intelligent, innovative and frugal. This is true of all the Chandrayaan launches. The second unique thing is that the systems that went into the making of the spacecraft were a great symbol of aatmanirbharta. It was all developed, designed and perfected in India, whether it was the electronics, the propulsion, the controls, the sensors or the other systems. The third thing was that we learnt from the limitations of the earlier two Chandrayaan missions because any failure gives you much more understanding than success does. We ensured that we learnt from them and implemented the solutions. For that, the decision-making and management process was critical and our approach included inclusiveness, openness to review, taking suggestions from everybody, including the larger scientific community beyond ISRO. Also insisting that there be no compromise while conducting all the tests, analysing performance, studying all suggestions thoroughly, addressing shortcomings and implementing corrections. I told the team we won't go for a launch until there was 100 per cent satisfaction at all levels.

> "Our mission was to achieve a soft landing while ensuring minimal cost. It was a unique, intelligent, innovative and frugal plan"

Q. Interestingly, you term this as a failure-based approach as opposed to the success-oriented one for the previous launch. What does that mean?

Let me clarify that a failure-oriented approach is not of pessimism. What it means is that we do not assume normal performance of all systems but instead plan for all things that can and will go wrong to make our boundaries for performance wider than we have ever thought about. Normally, we test everything to what is called 3-sigma level or three times the distribution and deviations possible. But this time, we told the team to go for 6-sigma deviations, leaving potential for absolute failures of systems and engines, overcome them in flight and still land.

Q. You looked very confident in the final stages of the flight. Where did that sense of calmness come from?

I am not in the habit of getting excited. I have seen over 50 rocket launches in my career, with several ups and downs. My approach is that we have already done whatever we could do and can't do anything more. So, we must be ready for any kind of result and be able to handle failure if it happens.

Q. After Chandrayaan, what?

A lot of discussion is going on internally on what we can do further. Any mission to the moon should be based on the scientific goals that we set. Once all the Chandrayaan-3 data is in and analysed, there will be certain new questions that will need to be answered and we will have to derive new ways of doing them. Bring back some lunar soil, for instance, to study it better. Another thing under discussion is launching a large number of small satellites to study the moon. We are also involved in a joint programme with Japan's space agency, where we provide the lander and the Japanese the rover.

Q. How will the US-backed Artemis Accord, to which India too is a signatory now, help?

Whatever we have signed is part of the accord, not the Artemis Programme. The Artemis Programme is a project started by the US government for the return of human space flight missions to the moon to create a lunar gateway. As part of the accord, many nations, including India, have signed up with the US on a principle that is non-binding on either party. Both have agreed to follow certain rules and regulations, especially for sustainability, while exploring the moon and other bodies. Currently, being part of the Artemis Accord gives India certain privileges, including access to US technology, so that we can build more complex systems. It could be a big game-changer as far as technology transfer from the US to India is concerned, including for our private sector.

Q. There is renewed interest in the moon. Apart from America, the Chinese and the Russians as well as a host of other countries, are preparing to launch missions. What explains it?

> "Ultimately, our aim is to recover rockets, as SpaceX does, and also meet the future demand for heavy-lift vehicles"

Earlier, going to the moon was all about geopolitical competition and projection power and prowess. The cost of going to the moon too was extremely high. Today, it is not. The technology now is much more advanced; we can do robotic experiments better than what Apollo or the Soviets could. The other aspect is that human beings want to explore the universe, and the moon is a good staging ground for it. Interplanetary explorations, such as to Mars and Venus, need a reasonably long-term base on the moon.

Q. The Russians have rockets that can send a lander to the Moon within days rather than weeks as we do. As do the Americans. What do we need to do to upgrade our capabilities?

We need to have new propulsion technologies of course. Currently, we depend on solid, liquid and cryogenic motors, but if we have to really make it big in terms of launch capability, then we have to have high-pressure liquid engines that can lift a 50-tonne payload instead of the current 6-10 tonnage. We need to build one such engine and then make a cluster of them to provide the necessary thrust to carry the higher tonnage. Ultimately, our goal is to recover rockets, like SpaceX does, and also meet the future demand for heavy-lift vehicles.

Q. The Modi government has opened up space for greater private participation, including to build launchers and satellites. What role will ISRO play?

When you look at NASA, it already had a solid defence industrial sector working to develop space systems in the US. But, in India, ISRO is doing all the space work, including design capability and getting the manufacturing done in both public and private sector industry. With the Union government opening up space, we want to make space a commercially attractive venture. Unless it is profitable, private companies won't take the risk. So, we have to look at the many ways to do so, but ISRO must remain a technology developer of knowledge, supporter of this knowledge and an enabler for the private sector. Big players in India, who have enough resources and wealth, like L&T, the Tatas and Adanis, should get into the space business. We must also encourage young entrepreneurs to build startups for space. Thirdly, apart from rocket- and satellite-building, there is a lot of money in space application and downstream work. If you look at the space economy, then commercial rocket-launching is 15 per cent of the business, and satellite-building around 15-20 per cent. So, almost 60-70 per cent of new business is being generated in space applications and downstream activity. This is a slow transition, and ISRO has to support it. ■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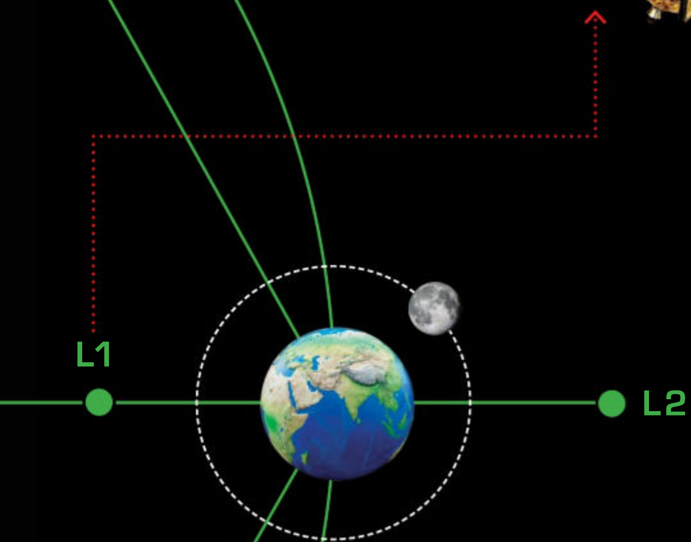
INDIA'S NEW SPACE AMBITIONS

AFTER THE CHANDRAYAAN TRIUMPH, ISRO IS NOW EYEING THE SUN, VENUS AND A MANNED SPACEFLIGHT. MEANWHILE, INDIA'S FLEDGLING PRIVATE SPACE INDUSTRY IS RARING FOR A PIECE OF THE PIE

BY RAJ CHENGAPPA



ADITYA L1 THE SOLAR MISSION

- It is the first space-based Indian mission to study the Sun
- The spacecraft will be placed in a halo orbit at the Lagrange Point 1 (L1)*, 1.5 million km from Earth
- After launch in Sept. 2023, it will take four months to reach the orbit
- Its life will be about five years, during which it will continuously view the Sun without any eclipses

THE OBJECTIVES

- The spacecraft will carry seven payloads to observe the Sun's photosphere, chromosphere and corona, using electromagnetic, particle and magnetic field detectors
- Will mainly study the problem of coronal heating, coronal mass ejection, pre-flare and flare activities and their characteristics

**Lagrange points (L1-L5) are positions in space where the gravitational pull of the Sun and Earth equals the centripetal force required for a spacecraft to move in tandem, allowing it to observe the Sun continuously without consuming too much fuel*

Graphic by TANMOY CHAKRABORTY

Having conquered the moon, the Indian Space Research Organisation (ISRO) is now trying to find its place under the sun. Even as the Chandrayaan-3 lander and rover were busy carrying out their scientific tasks on the lunar surface, other ISRO scientists and engineers were focusing on preparing the Aditya L1 spacecraft for its long journey to study the Sun. India's first mission to explore our nearest star works on the same principles as the Chandrayaan mission, where ISRO deployed innovative methods and ensured frugality in financial resources. America's National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have already carried out over 20 scientific space missions to the Sun, but ISRO, as it did with Chandrayaan, wants to come up with its own unique discoveries. Especially on the composition of the Sun's corona, photosphere and chromosphere. The space organisation hopes to do so by using the scientific instruments aboard Aditya to measure the solar electromagnetic fields and particle ejections that could shed new light on its behaviour.

The other major interplanetary project on ISRO's radar is sending an orbiter to Venus to study the planet's composition and atmosphere. Again, only a handful of countries have sent space probes to the planet nearest to us after Mercury.

These are not the only projects that are keeping many an ISRO scientist awake at night. Work is going on feverishly in its various laboratories across the country to realise ISRO's most ambitious mission yet: putting three Indian astronauts into orbit by indigenously building a 'human-rated' rocket launcher and crew module to fly them into space and bring them safely back to Earth. Called Gaganyaan, the mission requires ISRO to achieve mastery in a dozen new space disciplines, including mimicking Earth-like conditions in its crew module for the astronauts to stay on for several days and conduct experiments in zero gravity. The space agency is also testing a crew escape module that can eject the astronauts to safety in the event of a catastrophic failure of the launch vehicle that could endanger the lives of the astronauts at the launchpad during lift-off.

Meanwhile, the three astronauts for the mission have already been selected. All Indian Air Force pilots, they are undergoing the rigorous training required for being rocketed into space at 10x the speed of sound and then living in zero gravity conditions. Only three nations—the US, Russia and China—have sent up their own crewed spacecraft so far. Says ISRO chairman S. Somanath, "Many of the systems are new and we face a lot of technical challenges in realising them. We have to do multiple tests because the confidence-building process is very important. We will first test out all systems using unmanned flights, including sending a robot, before we launch our own astronauts into space. It has to be failure-proof because lives are involved."

In all these missions, ISRO is focusing on doing what it does best—technological innovation in a cost-effective manner. Aditya is a good example of how ISRO achieves this. To research the Sun, the agency will launch the spacecraft to an orbit 1.5 million km from Earth, or three times the distance from the Moon. Yet, with the Sun 150 million km away, Aditya will be only one per cent closer to it than Earth is. The plan is to place Aditya in the halo orbit around the Lagrange Point 1 or L1 where the gravitational pull of the Sun and Earth equals the centripetal force required for a spacecraft to move in tandem. This allows the spacecraft to observe the Sun continuously without consuming too much fuel. To get to the chosen Lagrange Point, ISRO is modifying its workhorse launcher PSLV to give it extra boost and put Aditya on track to get there. Further, as M. Sankaran, director, UR Rao Satellite Centre (URSC), explains, the mission team is using what are known as gravitational superhighways in space to propel Aditya to its destination the same way as the Chandrayaan launchers used Earth's gravity to slingshot it to the lunar orbit, thereby conserving fuel. This entails complex navigation and guidance, but ISRO has the experience of having

INTERVIEW

"INDIA IS NO LONGER THE LESSER COUSIN"

DR JITENDRA SINGH, the *Union Minister of State for Science & Technology and the Departments of Space and Atomic Energy,* was present at Mission Control when the Chandrayaan-3 spacecraft made a successful moon landing on August 23. *Group Editorial Director* RAJ CHENGAPPA spoke to him on the importance of the lunar mission and the future of India's space programme. Excerpts:

Q. What would you say is the importance of Chandrayaan to India's space programme and to the world?

Firstly, scientifically speaking, Chandrayaan-3 is going to get us inferences, conclusions and pictures, which would be possibly the first of their kind, for the entire scientific community across the world. Secondly, it has very evidently established India as a frontline nation as far as space technology is concerned. I must commend Team ISRO for having worked day and night for this mission, doing rehearsals and trials. They were working as if preparing to appear for a competitive exam...and that is the reason they were so confident at the end of the day. The rest of the world was not, but they were.

Q. You were with the scientists at Mission Control during the moon landing. What were your thoughts?

We were very conscious of the fact that the

CHANDRADEEP KUMAR

entire descent is left to the wisdom of Vikram [lander]; so that is the test of how well you have trained this boy to handle the situation on his own. It is just like training a soldier and sending him to the front and leaving it to his decision. Also, we were accountable to the entire nation. More so to the Honourable Prime Minister because after Chandrayaan-2, he said that sometimes not being successful is a step towards being successful. That was a wonderful message. We had to live up to it. When [Vikram] landed successfully, all of us jumped out of our chairs and clapped. It was so spontaneous.

> **“The process of synergy is happening, and in just three years, we have more than 150 private start-ups in the space sector”**

Q. What are the next big things for the space programme?
Apart from Aditya-1, then Gaganyaan and Venus [orbiter] simultaneously, we are going to have a huge number of launches from the private sector. This also happened after the prime minister took the courageous decision to completely open up the space sector to private parties in the country. As a result, there is a quantum jump in our space missions. We now have a collaboration with virtually most of the countries. The best part of the collaboration with Russia and America is that we are no longer the lesser cousin. We are now equal partners and, in many ways, more than equal. For example, now we are lending services to America and Russia...we already earned more than \$170 million. We now do \$8 billion (Rs 66,000 crore) of business. But at the pace we are rising, India could go up to \$40 billion (Rs 3.3 lakh crore) by 2040 in the space sector, a recent report by a reputed agency has said.

Q. So you are saying the PM's decision in 2020 to open the space sector for private industry to manufacture rockets and satellites, instead of just ISRO, has been a game-changer?
Absolutely! I never hesitate to say this time and again. One thing is proven, there is no dearth of talent in India. We have talent, we have calibre and competence.... For too long, we unnecessarily had a veil of secrecy and confined ourselves to ISRO. This was no longer required. Now, in addition to the private industry investment, we have this whole ecosystem that includes the National Research Foundation legislation, which allocates Rs 50,000 crore to be spent with Rs 36,000 crore coming from the non-governmental sector.

Q. What would be the impact?
It is very progressive thinking because from now onwards, if we have to go, we have to go wholesomely. You cannot depend on government resources alone. If we have to visualise a global role for ourselves, then we have to have global parameters and a global strategy. That is what Americans are doing; NASA is no longer depending on government resources. The process of synergy is happening, and in just three years, we have more than 150 private start-ups in the space sector. So, we are heading towards a scenario where with little demarcation between public and private sectors, it will be a totally integrated approach.

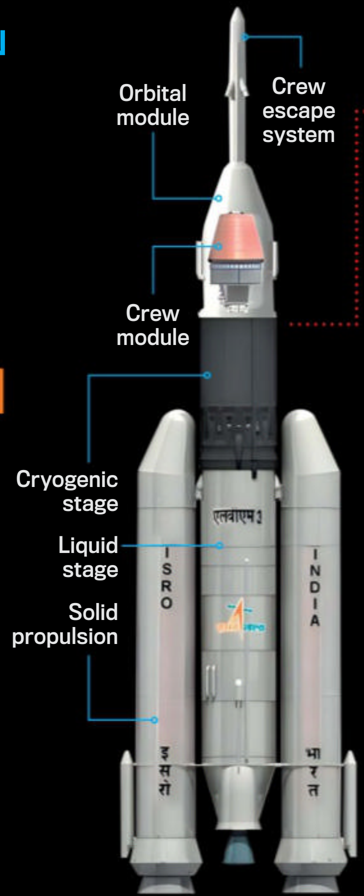
Q. Finally, why should we be spending on projects to the moon instead of development?
I am often asked this question, saying that it is a costly affair. A moon project is not. It is just Rs 600 crore; not even a fraction of what other countries are spending and just about what it costs to construct a section of a big bridge across a river. Even our expressways cost us more. So, one aspect is that we are very cost-effective. The second part is that if Chandrayaan-3 actually succeeds in discovering minerals and petroleum, all those things would be adding value to our lives even on Earth. Thirdly, the kind of esteem it gives to the nation. Especially if we are looking forward to playing a global role, we have to get global recognition. ■

GAGANYAAN

OUR FIRST HUMAN SPACE FLIGHT

THE MISSION

- Demonstrate India's human spaceflight capability
- Launch a crew of three members to an orbit of 400 km for a three-day mission
- Bring them back safely to Earth, by landing in Indian sea waters
- Planned launch: 2025-26



PRIVATE INVESTMENT WILL BE IMPORTANT IF INDIA'S SPACE SECTOR HAS TO EXPAND RAPIDLY. IT CANNOT DEPEND ON GOVT FUNDING ALONE

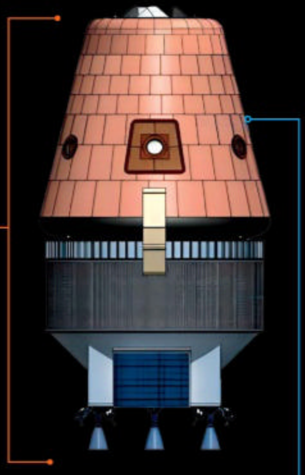
sent the Mangalyaan spacecraft to Mars when it was at a distance of close to 99 million km from Earth. However, to do so, it had to traverse 660 million km because of the orbit-raising manoeuvres it needed to make.

This expertise will allow ISRO to load a lot more instruments onto Aditya L1 to comprehensively study critical solar parameters that impact us on Earth. And why is that important? Because, as we all know, the Sun wields great influence on Earth with radiation, heat and continuous flow of particles called solar winds, in addition to magnetic fields that affect the entire solar system. Occasionally, there are explosive and eruptive events like Coronal Mass Ejections (CME) or solar flares that, among other things, trigger a magnetic storm near Earth and interfere with the functioning of space-based and terrestrial telecommunication systems. As Kiran Kumar, former ISRO chairman, says, "It is important that nations study such disruptive phenomena of the Sun, make sense of them and thereby enable early warning signals to Earth to minimise any damage these may cause." Kumar also points out how Aditya's orbital path will give the spacecraft an uninterrupted view of the Sun, enabling its instruments to study CME and solar coronal dynamics.

To allow Indian scientists to study such phenomena closely, Aditya is bristling with seven scientific payloads put together not just by ISRO but also by other major Indian scientific institutions. The Bengaluru-based Indian Institute of Astrophysics, for instance, has developed the Visible Emission Line Coronagraph (VELC) to study both the solar corona and CME dynamics. The Inter-University Centre for Astronomy and Astrophysics in Pune has built the Solar Ultraviolet Imaging Telescope (SUIT), which will capture images of the solar photosphere and chromosphere and measure its irradiance to throw new light on its composition. Ahmedabad's Physical Research Laboratory (PRL) has put together the Aditya Solarwind Particle Experiment (ASPEX), which along with the Plasma Analyser Package for Aditya (PAPA) built by the Space Physics Laboratory in Thiruvananthapuram, will study the solar wind and energetic ions, as well as their energy distribution. Two payloads—the Solar Low Energy X-ray Spectrometer (SoLEXS) and the High Energy L1 Orbiting X-ray Spectrometer (HEL1OS) to study the X-ray flares from the Sun—and another, the Magnetometer, to measure interplanetary magnetic fields, are built by two of ISRO's Bengaluru-based centres, namely the URSC and the Laboratory for Electro Optics Systems (LEOS), respectively. Aditya, in fact, is a good example of the phenomenal collaborative effort of scientific institutions that gives ISRO the cutting edge in whatever it undertakes.

Meanwhile, the most significant transformation ISRO is going through in its 54 years of existence is on account of the radical policy changes the Modi government has introduced in India's space sector. Prior to 2020, ISRO planned, designed and built all of India's spacecraft, be it rocket launchers, satellites or planetary orbiters. To its credit, the space agency engaged the private sector, but mainly to manufacture its sub-systems and assist it in assembling the spacecraft. In May 2020, however, in the midst of the Covid-19 pandemic, Prime Minister Narendra Modi threw open the gates of the space sector to comprehensive private participation. This included permitting private sector players to build and assemble their own rockets and satellites

KEY SYSTEMS



HUMAN-RATED LVM3

ISRO's heavy lift launch vehicle will launch the orbital module, including crew module (CM), to low Earth orbit of 400 km. It will also have a crew escape system to ensure that the CM along with the crew is taken to a safe distance in case of an emergency during lift-off

ORBITAL MODULE

Will orbit Earth and comprises the CM and Service Module (SM). It is equipped with a state-of-the-art avionics system with adequate redundancy, considering human safety. SM will be used for providing necessary support to CM while in orbit

CREW MODULE

It is the habitable space with Earth-like environment in space. It houses the crew interfaces, human-centric products, life support system, avionics and deceleration systems. It is also designed for re-entry to ensure safety of the crew during descent

Graphic by TANMOY CHAKRABORTY

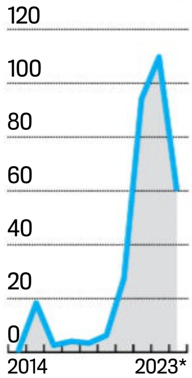
INDIA'S NEW SPACETECH ECOSYSTEM

SKY IS THE LIMIT

Propelled by privatisation since 2020, the Indian space technology sector is on an upward trajectory

7th
India's rank in terms of funding within the international spacetech ecosystem in 2023

INVESTMENT TRENDS



*(In $mn; *till July)*
Source: Tracxn

TOP 3 COMPANIES*

Pixxel	97.1
Skyroot	72.3
AgniKul	34.8

**Based on total funding*

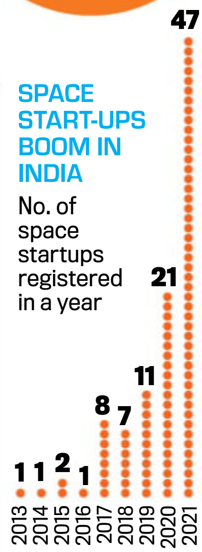
TOP 5 FUNDING DEALS

Skyroot	51
Pixxel	35
MTAR	24.4
AgniKul	20
SatSure	14.5

(Since 2020; in $mn)

SPACE START-UPS BOOM IN INDIA

No. of space startups registered in a year



Source: Startupindia

and use ISRO's extensive facilities, including launch pads and laboratories, to do so. A coordinating government body called the Indian National Space Promotion and Authorisation Centre (IN-SPACe) chaired by Pawan Goenka, ex-CEO of Mahindra & Mahindra, was formed for private players to interface with ISRO and use its facilities. In April this year, the Union government formalised the process by announcing the Indian Space Policy 2023 to institutionalise private sector participation.

Already, the policy is yielding results with the new private space tech ecosystem for commercial rocket launchers and satellites expanding at a meteoric pace. Over 150 space start-ups have been set up and many, like Skyroot, Pixxel and AgniKul, have received substantial foreign funding. In November 2022, Skyroot became the first Indian private sector company to indigenously build a rocket launcher and successfully launch it into sub-orbital space from Sriharikota. The company has received an impressive $51 million (Rs 421 crore) in investment since 2020 and a total of $72.3 million (Rs 597 crore) since its inception five years ago. Overall funding for space start-ups has grown exponentially, attracting $112 million (Rs 925 crore) in 2022. Funding to private entities has already touched $62 million (Rs 512 crore) this year, a 60 per cent rise over the same period last year. Says Jitendra Singh, the Union minister of state for science & technology and the departments of space and atomic energy, "All this is because the prime minister took the courageous decision to completely open up the space sector to private entities in the country. For too long, we had unnecessarily put a veil of secrecy over our space activities and confined ourselves to ISRO. This was no longer required. As a result, there is a quantum jump in our space missions." (See interview, "*India is no longer the lesser cousin*".)

Private investment and initiatives will be important if the space sector in India has to expand rapidly, because it cannot depend on government resources alone to fund projects. As Singh points out, "If we have to visualise a global role for ourselves, we need global parameters and a global strategy. That is what the US government did and NASA, its space agency, no longer depends on government sources for funds or expertise to execute missions." Of course, it will take Indian industry a while to reach where, say, Elon Musk has with SpaceX and Jeff Bezos with Blue Origin in the US. According to Somanath, the satellite and launch market constitutes only 30 per cent of the world's $360 billion (Rs 29.7 lakh crore) space economy; it is space applications that account for 70 per cent of the business. And this is where Indian private companies can make a major foray. India's current share of the space business is around $8 billion (Rs 66,000 crore) or just over two per cent of the total. By 2040, if all goes well, per global consultancy firm Arthur D. Little, India could realise its potential of being a $40-100 billion space industry and become a major global player. That is a mission India should pursue at rocket speed. ■