YOJANA

Azadi Ka Amrit Mahotsav

MAY 2023 | A DEVELOPMENT MONTHLY | ₹ 22

TECHADE

LEAD ARTICLE

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INNOVATION IN SPACE TECH

The exploration of space has always been a driving force for technological innovation, pushing the boundaries of what is possible and opening up a myriad of opportunities for research and development. From the early days of the space race to the present day, the pace of innovation in space technology has been rapid and transformative. Space applications, transportation systems, and infrastructure are a few verticals of the ISRO programme that have witnessed many technological innovations. It is actively pursuing the maiden human spaceflight mission - Gaganyaan to send astronauts to space and safely return to Earth.

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In our country, the Indian Space Research Organisation (ISRO) has been at the forefront of space technology and exploration since its inception. On 21 November 1963, the first rocket took off from Thumba, a fishing hamlet near Thiruvananthapuram, announcing the birth of India's space programme. The then rocket, payload, radar, and computer all that was required for the first launch, came from outside the country.

Over the years, leveraging its key resources, the organisation has made several strides in space technologies, making India a major player in the global space arena. In ISRO, the evolution of space technology and innovation had taken place in various technological frontiers. It is beyond the scope of the present article to touch upon every innovation in space technology that has taken birth at ISRO in the journey of 53+ years.

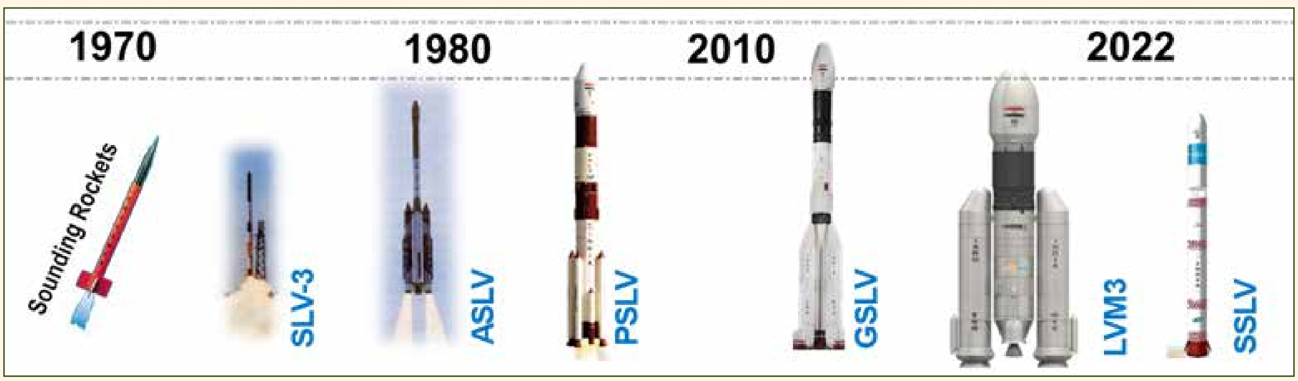

Figure 1: Evolution of ISRO rockets

Nevertheless, the spectrum of technological innovations, in this article, will cover the major verticals of Space Transportation System, Space Infrastructure, Space Science and Inter-Planetary Missions, Space Applications, Human Space Exploration, Space Robotics, Artificial Intelligence, Quantum Technologies, among others.

SPACE TRANSPORTATION SYSTEM

The 1970s marked the beginning of space transportation system with the development of solid-propulsion-based Sounding Rockets, which are capable of putting 30 kg of payload in 120 km of altitude, soon followed by the subsequent development of first generation launch vehicles, i.e., Satellite Launch Vehicles (SLV) and Augmented SLV (ASLV) with the induction of liquid-propulsion technology. The integration of solid and liquid propulsion and the development of various key technologies in the areas of Aerodynamics, Manufacturing, Composites, Mission Simulation, Avionics, Pyros, Mechanisms, Materials, Structural Engineering, Payload Integration, and System Reliability have resulted in the development of the second generation workhorse launch vehicle, which is none other than the Polar Satellite Launch Vehicle (PSLV), with the capability of placing a 1700 kg payload into polar orbit.

The indigenous development of a Cryogenic propulsive engine was the major technology leap in the development of third generation rockets i.e., GSLV launch vehicles, which have the capability of placing a 2000 kg payload in Geo-Synchronous Transfer Orbit (GTO).

Launching of high-throughput communication satellites necessitated the development of a further advanced launch vehicle, i.e., Launch Vehicle MK3 (LVM3). Powered by the world's 3rd largest solid boosters, high-capacity liquid and cryogenic engines, LVM3 has the capability of putting 4000 kg payload in GTO.

The latest member of ISRO's rocket family is the Small Satellite Launch Vehicle (SSLV), a three stage launch vehicle. Solid stages and a liquid propulsion based velocity trimming module made SSLV capable of launching a 500 kg satellite into a 500 km planar orbit in a quick turn-around time. Figure 1 shows the generations of ISRO rockets, from the sounding rocket era to the latest SSLV timeline.

> **Successful findings of water on the Moon was the scientific breakthrough achieved by Chandrayaan-1. Then, Rover and Landercraft technologies were developed, leading to the conception of a second mission to our nearest celestial neighbour. Chandrayaan-2 mission was altogether a highly complex mission, consisting of an Orbiter, Lunar Rover and Lunar Landercraft, as compared to its predecessor.**

SPACE INFRASTRUCTURE

Like the space transportation system, the early 1970s were the formative years of the Space Infrastructure of ISRO, which led to the foundations for design, building and operation of spacecraft. Soon, the first satellite of the country, 'Aryabhata' was realised and launched on 19 April 1975. Subsequently, experimental missions like Bhaskara and APPLE were executed and geared towards remote sensing, meteorology, and communications technologies.

Further momentum was gained with the indigenous development of key technologies for spacecrafts such as Advanced Propulsion, Power Systems, Thermal Systems, Deployable Structures, Space Bus Systems, Communication Systems, Ground Infrastructure, Optical, Microwave, Scientific & Communication Payloads, Unfurlable Antennas, High Throughput Satellite Systems, Multi-Spectral Optical Satellite Systems, High Resolution Cameras, Multi-Wavelength observations of the Universe, Stationary Plasma Thruster etc., for the self-reliance in spacecraft technology.

Capability in the remote sensing has grown from the coarse resolution of 1 km to the fine resolution of 28 cm with day & night and all-weather capability. The communication transponders have also proportionally grown from a mere single unit to 317 numbers. Altogether, ISRO has mastered the capability of making satellites of 2000 kg with 1 kW power to 6000 kg with 14 kW power, operating in various frequency bands and with wide, shaped, and highly focused spot capability for communications, sub-metre resolution, optical, multi-spectral, and microwave imaging for earth observations, and progressing from payload-based navigation solutions to a satellite constellation - NavIC (Navigation with Indian Constellation). The present space infrastructure includes 25 Earth observation satellites, 22 communication satellites, 7 navigation satellites, 2 space science satellites and experimental, small and student satellites. The evolution of satellites in ISRO is outlined in Figure 2.

SPACE SCIENCE AND INTER-PLANETARY MISSIONS

Entrusted by confidence and technical expertise gained from satellites and launch vehicle technologies, ISRO has sailed successfully to the reach of the Moon and Mars, opening the era of planetary explorations and beyond. Chandrayaan-1, the first lunar orbiter mission has brought new experiences in hosting international payloads, calibration, data interpretation, adopting global standards in science data formats, etc. The science outcomes of the maiden mission have provided

Figure 2: Evolution of ISRO satellites

new perspectives about the Moon. Successful findings of water on the Moon was the scientific breakthrough achieved by Chandrayaan-1. Then, Rover and Landercraft technologies were developed, leading to the conception of a second mission to our nearest celestial neighbour. Chandrayaan-2 mission was altogether a highly complex mission, consisting of an Orbiter, Lunar Rover and Lunar Landercraft, as compared to its predecessor.

ISRO continues to explore Mars with the first ever interplanetary mission to the red planet, called Mars Orbiter Mission (MOM), aka Mangalyaan. It made India the first Asian nation to reach the Martian orbit and the first nation in the world to do so on its maiden attempt. MOM explored Mars' surface features, morphology, mineralogy, and Martian atmosphere with five onboard scientific instruments. The key technologies required for designing, planning, management and operations of an interplanetary mission were developed during MOM, which comprised - Orbit raising Manoeuvres, Trans-Mars Injection, Trajectory Correction Maneuvers, Mars Orbit Insertion, Development of Force Models and Algorithms for Orbit and Attitude (Orientation) Computations and Analysis, Navigation in all phases, etc. The spacecraft was monitored from ISTRAC, ISRO-Bengaluru with support from the Indian Deep Space Network (IDSN) antennae in Karnataka. MOM has yielded unprecedented technical insights into the Martian atmospheric composition and many other aspects of the planet.

The multi-wavelength space astronomy mission, AstroSat has served astronomers from nearly 50 countries. One of the breakthrough findings of the mission is the detection of UV emission from star formation in a galaxy that is 9.4 billion years away, providing the first measurements in the redshift range, near to the peak of the cosmic star-formation history of the Universe. Figure 3 shows a few glimpses of ISRO's space science and planetary mission.

Figure 3: Glimpses of ISRO's space science and planetary missions

SPACE APPLICATIONS

Space Applications is yet another vertical of the ISRO programme, which has witnessed many technological innovations. Earth Observation (EO) applications are institutionalised across many user Ministries/Departments, towards National security, Agriculture, Agro-forestry, Disaster management, Fishery, Land Use Land Cover (LULC), Resource Mapping, Planning, Monitoring & Evaluation and decision support for major Flagship Programmes of the Government.

In order to meet the gamut of aforementioned requirements for remote sensing/EO applications, a great deal of development had taken place in ground infrastructure and imaging technologies.

Ground technologies for tracking multiple objects in space, including the establishment of multi-object tracking radar, an integrated multi-mission ground segment for earth observation satellites, Polarimeteric Doppler Weather Radar, state-of-the-art advanced ground station for Earth Observation satellites at Bharti station, Antarctica Multi-Frequency Earth Stations, and a Distress Alert Transmitter have facilitated the uninterrupted

Figure 4: PAD Abort Test (PAT-01) for Gaganyaan

usage of satellite services.

The revolution in imaging technologies such as Pushbroom, 3-Tier Imaging, Step-Stare, Stereo Imaging, Scatterometer, Synthetic Aperture Radar (SAR), Ground Penetrating Radar (GPR) Altimeter, TDI imaging, VHR imaging, etc., in the domain of Earth Observation served to accomplish 47 missions with capabilities of spatial resolution from 1 km to 28 cm, temporal resolution of 24 days to 2.5 days, and spectral resolution of 7 bits to 14 bits.

HUMAN SPACE EXPLORATION

Human Space Exploration is the latest entrant to programmatic verticals of ISRO. At present, ISRO is actively pursuing the maiden human spaceflight mission - Gaganyaan to send astronauts to space and safely return to Earth. Gaganyaan is yet another very complex mission, involving development of major technology elements such as human-rated launch vehicle, Crew escape systems, Habitable orbital module, Life support system, Crew management activities for the safety of humans onboard, to name a few. Demonstration of re-entry flight of Crew Module i.e., Crew Module Atmospheric Re-entry Experiment (CARE) mission and Pad abort test for crew escape systems, and testing of human-rated launch vehicle propulsive stages i.e. solid boosters, liquid and cryo engines have been successfully accomplished. A new vehicle i.e., Test Vehicle (TV) has been developed to test critical crew associated systems. ISRO conducted a major development test, 'Integrated Main Parachute Airdrop Test (IMAT)' of the crew module deceleration system to simulate different failure conditions of the parachute system before it is deemed qualified to be used in the first human spaceflight mission. Gaganyaan is at an advanced stage of its mission realisation.

> **ISRO has been actively pursuing several R&D programmes related to Space Robotics -Vyommitra (Humanoid robot), Lander and Rover for Chandrayaan-3 mission, On-orbit Satellite Refueling, Planetary Rock Sampler, Space based robotic manipulator, Robotic arm based umbilical systems, 3D printing in Space, to name a few.**

TECHNOLOGY INNOVATION CONTINUES…

Apart from the aforementioned five major programmatic verticals of ISRO, strides in space technology innovation continue in the thrust areas of Reusable Launch Vehicles, Stage Recovery and Reuse, Vertical Take-off Vertical landing (VTVL), LOX-Methane Engine, Air breathing/ Hybrid Propulsion, 3D printing, Artificial Intelligence, Space Robotics, Humanoid robots, On-orbit servicing, Advanced Materials & Manufacturing, Chemicals and Energy Systems, miniaturised Avionics system, Advanced Inertial systems, Low Cost Spacecrafts, Inter Satellite Link (ISL) Networks, Space Based Solar Power, Quantum Communication, Quantum Radar, Electric Propulsion, Advanced Scientific Payloads, Space Based Surveillance, Advanced Data processing, Atomic Clock, Travelling Wave Tube Amplifiers, In-Situ Resource Utilisation, Flexible Satellite Payloads, Inter-planetary Space Exploration, Space Tourism, Low-temperature Energy Systems, Intelligent Satellite, Self-destructing Satellite, Space Bio-mimetic, Technologies for sustained Human space missions namely, Regenerative Life support systems, Rendezvous and Docking, Inflatable habitats, Human factor and Engineering studies, etc.

In an effort to develop technologies for low-cost access to space and space travel, ISRO conceived a Reusable Launch Vehicle (RLV) programme to develop space planes and shuttles that can ascent to orbit, stay there, re-enter, and land on a runway like an aeroplane. Having accomplished suborbital flight and sea landing in 2016, recently, ISRO made a significant development in RLV technologies with RLV landing experiment (RLV-LEX) demonstrating autonomous landing of a winged vehicle on a runway. The experiment was demonstrated at ATR-Chitradurga, Karnataka, on 02 April 2023. Currently, ISRO is working on the Orbital Re-entry Experiment (ORE) which will be carried out with RLV flown atop an updated version of GSLV.

Space data economy, aided by new data churning, artificial intelligence, machine learning tools, is new oil for the service of advanced livelihood requirements like smart city, smart manufacturing, and supply chain, among others.

Air breathing propulsion with reusable capability is yet another key technological elements for a cost-effective futuristic space transportation system. ISRO is actively pursuing the development of technologies for an Air Breathing Two Stage to Orbit (AB TSTO) vehicle under the Air Breathing Propulsion Project (ABPP). The successful demonstration of 'scramjet operation' in flight conditions in the ATV-D02 Scramjet demonstration flight, in 2016, was a major technological boost in this regard. The ISRO's current focus is on the development of critical technologies towards the realisation of a vehicle-integrated scramjet engine called the Hypersonic Air Breathing Vehicle with Airframe integrated system (HAVA). Successful testing of the engine was accomplished in December 2022.

It is worth noting that for the first time in the country, ISRO achieved a breakthrough demonstration of free-space Quantum Communication over a distance of 300 m using the Prepare & Measure Protocol and Quantum Entanglement protocols. A number of key technologies were developed indigenously to accomplish these feats, including Entangled-photon source, Polarization compensation technique, gimbal mechanism systems, cryptographic software suite.

Figure 5: Spin-Off/ Societal Applications

> **There is a requirement for the close integration of IT and space-based data for providing digital solutions in the future. Big data analytics in decision-making and human-machine symbiosis will play a key role in providing a governance solution.**

ISRO has been actively pursuing several R&D programmes related to Space Robotics -Vyommitra (Humanoid robot), Lander and Rover for Chandrayaan-3 mission, On-orbit Satellite Refueling, Planetary Rock Sampler, Space-based robotic manipulator, Robotic arm-based umbilical systems, 3D printing in Space, to name a few.

ISRO has innovatively used the spent 4th stage of PSLV for carrying out scientific experiments under a nick name called POEM (PSLV Orbital Experimental Module). It provides a microgravity platform for conducting various scientific experiments in space. The opportunities are open for academic institutions and industries.

Space data economy, aided by new data churning, artificial intelligence, machine learning tools, is the new oil for the service of advanced livelihood requirements like smart city, smart manufacturing and supply chain, among others. Every day, 100s of Terabytes of satellite data volume are downloaded from EO satellites, communication satellites and navigation satellites for the service of mankind on earth. Even the advent of electrified and autonomous cars demands very high data usage. It is estimated that one autonomous car consumes 4000 gb data per day which is roughly the amout of data used by 2666 internet users.

The applications of satellite data in Smart cities are increasingly high, and data consumption becomes extremely enormous in connected cities. The applications include monitoring critical infrastructure, weather, location, navigation, etc. There is a requirement for the integration of satellite telecommunication, EO and navigation platforms. Today's smart manufacturing involves end-to-end digitally connected supply chain, which enables prediction, raw material forecasting and selecting optimised routes to deliver product in less time while integrating all the stakeholders.

There is a requirement for the close integration of IT and space-based data for providing digital solutions in the future. Big data analytics in decision-making and human-machine symbiosis will play a key role in providing a governance solution. India has a flourishing software industry and a self-reliance space industry with deep internet penetration, which form the three pillars of technology enabled governments.

The technology developments in the space sector have also reaped the benefits directly to Societal Applications as spin-offs. In this genre, mention can be made of Ventricular Assist Devices, Microprocesser-Controlled Limbs, and Medical Ventilators.

With the advent of space sector reforms, the participation of Non-Governmental Entities (NGEs) in space activities is encouraged to foster the space ecosystem and make space a driver for the country's scientific temperament and overall development.

As can be seen, in the country, the field of space technology has witnessed an unprecedented amount of innovation over the past few decades, and ISRO has played the role of a gravity organisation to unlocking the secrets of the cosmos and advancing human knowledge. As we look towards the future, innovations in space technology will undoubtedly pave the way for new discoveries and advancements, opening up new frontiers for exploration and expanding our understanding of the universe. Ultimately, innovation in space technology is not just about pushing the boundaries of science and technology, but also about expanding the horizons of our understanding of the universe and the world we live in. ❑