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India's Small Satellite Mission:

Time for the Next Leap Forward

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About the Author

Narayan Prasad is the co-founder of Dhruva Space, a Bengaluru based new space company established in 2012 with a vision to lead the turn-key satellite development industry in India. He is an EGIDE scholar who holds a an M.Sc in Space Technology, Sweden and M.Sc in Space Techniques and Instrumentation, France under the Erasmus Mundus Space Master programme.

List of Abbreviations

AIS	Automatic Identification of Ships
ASAT	Anti-Satellite
ASLV	Augmented Satellite Launch Vehicle
BSTI	Basic Space Technology Initiative
CNES	French Space Agency
COTS	Commercial-Off-The-Shelf
CSR	Corporate Social Responsibility
ELINT	Electronic Intelligence
EO	Earth Observation
ESDN	Edison Demonstration of Smallsat Networks
GSD	Ground Sampling Distance
IMS	Indian Mini Satellite
INSAT	Indian National Satellite System
ISRO	Indian Space Research Organisation
IRNSS	Indian Regional Navigation Satellite System
IRS	Indian Remote Sensing
LEO	Low Earth Orbit
MHRD	Ministry of Human Resource Development
NLAS	Nano-satellite Launch Adapter System
RTP	Rohini Technology Payload
SDR	Software Defined Radio
SME	Small and Medium Enterprises
SROSS	Stretched Rohini Satellite Series
UNOOSA	United Nations Office of Outer Space Affairs
UoSAT	University of Surrey Satellite

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Executive Summary

India has always given importance to the development of space technology for peaceful purposes. The Indian space programme is one of the biggest national space programmes in the world, which has transitioned from its purely research orientation in the 1960s to a commercial orientation in the 1990s. The Indian Space Research Organisation (ISRO), in its early years, developed small satellites (for example, the Rohini satellite series) which carried out several scientific experiments. Since then, the requirement of space-based citizen services has led ISRO to build larger satellite systems such as the IRS (Indian Remote Sensing), the INSAT (Indian National Satellite System) and the IRNSS (Indian Regional Navigation Satellite System) for mapping, navigation, meteorology, communications, among other services.

This paper explores the extent of proliferation of small satellite related activities in India. Although satellites below 1,000 kg are generally referred to as small satellites, the paper considers only satellite platforms with a mass of less than 150 kg, due to their proliferation across the world in the past decade. An effort has been made to draw parallels from across the globe at various levels in the current use of small satellite platforms, be it in academia, civilian space agencies, industries or defence establishments.

The study indicates that several small satellite projects at Indian universities have been delayed due to lack of integration into academic

activities/curriculum, and the absence of reasonable employment for graduating students who lead the projects. One of the main hurdles in running such academic missions in India is the lack of a programmatic approach to the development of small satellites. Most academic missions in India face this critical hurdle due to the lack of a policy for reasonable employment within the small satellite programme or industries based on such programmes. Universities need to consider providing credits to students working on small satellite projects. There is a need to embed practical education into academic grading which would encourage more students to join such projects. A case has also been made for a dedicated funding model for the development of small satellites at academic institutes in the country, which can be led by a federal department such as the Ministry of Human Resource Development (MHRD). Parallels have been drawn to showcase the necessity of encouraging the development of Small and Medium Enterprises (SMEs) which build on the intellectual property generated by such programmes. There is a need not just for incubation/office support, but also for establishing a space systems laboratory that can work independently and is capable of delivering turnkey solutions.

The Indian Mini Satellite (IMS) satellite series was envisaged by ISRO as a platform for carrying payloads for earth observation, space science research, atmosphere and ocean related studies. The stated objective was to develop advanced miniaturised technologies to achieve the performance of IRS class satellites on miniaturised platforms. Although the bus has capabilities for producing distributed missions, it has not found any traction due to the lack of a dedicated programme on small satellites. A comparison with other space agencies including NASA, ESA and JAXA (the space agencies of the US, Europe and Japan) has been drawn to present the case for small satellite platforms which have been used as testing grounds for innovative science and engineering. A case has been made for a dedicated programme on small satellites with a transparent timescale which can spur interest in academia and industry to explore several mission avenues of research and commerce.

Although several tech transfer initiatives have been successful, the Indian space programme, unlike some of its developed country counterparts across the globe, has not seen the emergence of turnkey solution providers in the satellite segment. There is a fundamental need for public-private partnership mechanisms to establish an environment to provide turnkey solutions within the country. Based on such initiatives, the current space industry in India can emerge as an integrator, which would allow ISRO to play the role of vendor/facilitator to users for turnkey missions. The study presents a case for small satellites to be effective platforms to create umbrella programmes (e.g. Hodoyoshi in Japan, Myriade in France) which will allow the industry to play turnkey solutions provider under the guidance of the established space programme. This will benefit the Indian space industry, enabling it to leverage Indian labour and material cost advantages to provide space technology/services globally.

The Technology Perspective and Capability Roadmap of the Headquarters Integrated Defence Staff, Ministry of Defence, decides in part the space based requirements of the armed forces. Such military services/operations take longer if pursued through ISRO, which has the burden of delivering civilian services as well. Distribution/separation of civilian space interests and military space interests has been in force in the launch programmes, and the same in further development of the space segment will enable the armed forces to leapfrog ahead. Due to the lack of a dedicated space based defence programme in the country, the armed forces have to rely on ISRO, a civilian organisation with a clear mandate to exploit the civilian/societal benefits of outer space. A dedicated programme within the armed forces would complement ISRO's satellites and would offer the armed forces more options in integrating the dedicated military satellites into the service of specific operations/applications more smoothly. This is also imperative for autonomy in rapid development and deployment; it is better for data and operational security. Overviews of small satellite based missions representative of security/military interests have been presented.

The present work looks at the current state of space activities within India at various institutions and identifies the opportunities alongside the gaps. Specific conclusions and recommendations have been made that can not only impact the current state of development and usage of small satellite platforms/activities, but can also fundamentally change the approach to development of missions, considering the specific interests of each of these various institutions.

1. Understanding Small vs. Large Satellites

The advent of the space age saw the development of small satellites mainly due to the constraints of launch vehicles in sending heavy payloads into orbit. Sputnik, the first satellite launched on 4 October 1957, was a 58.0 cm-diameter aluminium sphere weighing 80 kg.[1] The world's first commercial communications satellite (Intelsat 1) was a small satellite with a launch mass of 68 kg.[2] These first satellites were experimental. As the capacity to launch heavier payloads increased, satellite based services required manufacturers to develop satellites that were substantially bigger to provide reasonable space-based services to a large base of users.

In today's context, how small are small satellites? A study by the International Academy of Astronautics breaks down the category into:[3]

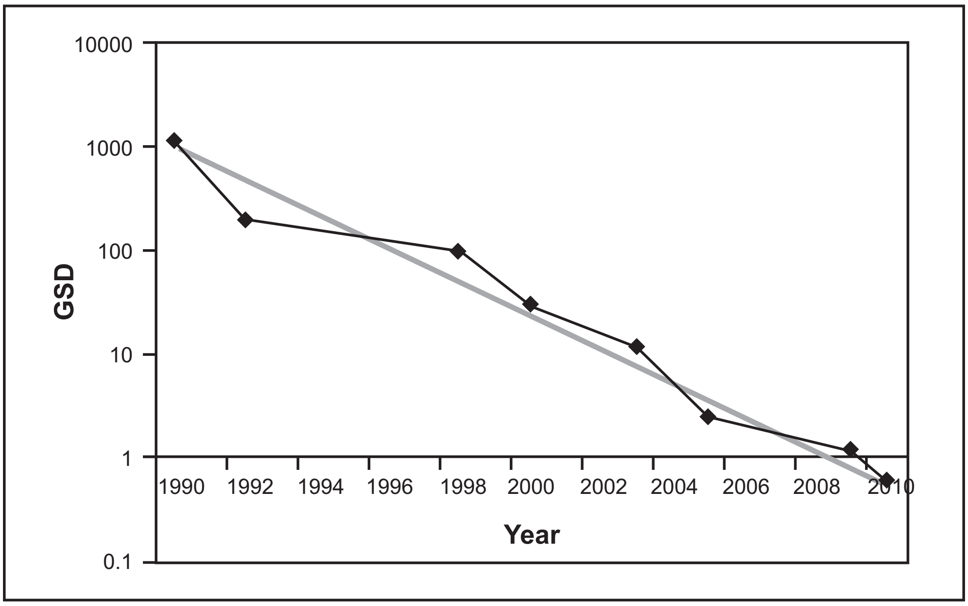
- Mini satellites - less than 1,000 kg
- Micro satellites - less than 100 kg
- Nano satellites - less than 10 kg
- Pico satellites - less than 1 kg

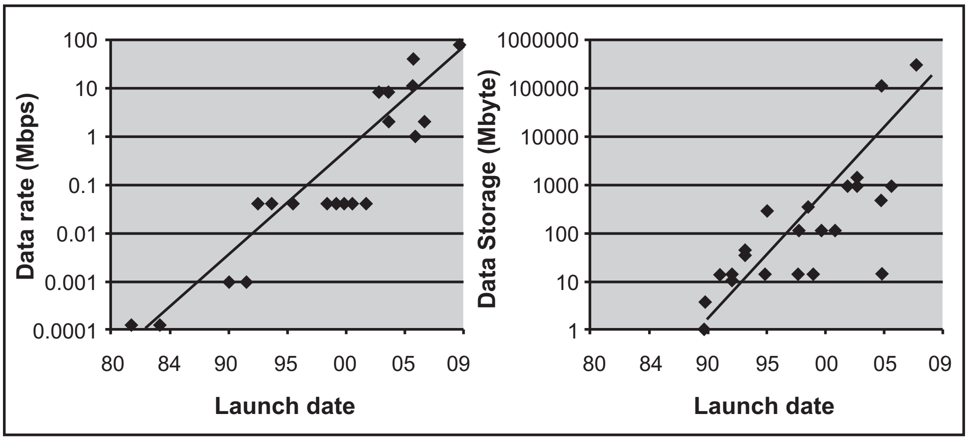
Small satellites should not be confused with systems that replace large satellite based services/operations. The small vs. large satellites debate is not one of capability or capacity. It is about their ability to complement each other's platforms and overcome existing disadvantages. While large satellites, such as the geostationary satellites providing communications services are designed to last over 15 years, small satellites are often missions with a two to five year timeframe. Hence, the approach to designing and building small satellites is different. Small satellites take advantage of the latest technology developments, arguably testing them for the first time in space, leading to further miniaturisation of subsystems/components, development of micro/nano-technologies for sensors and instruments which allow the design of dedicated, well-focused high-performance missions.

It is important to understand that the approach to design, development and on-orbit operations of a small satellite is fundamentally different. While there are very few large satellites that are experimental in nature, most small satellites are placed in orbit to gain space heritage or to conduct new experiments/test new technology at a fraction of the cost of building a large satellite. Driven by user requirements, large satellites/satellite systems are designed to provide availabilities close to 100 percent. Risks cannot be taken while developing such spacecraft. Hence developers need to bank on technologies that have had extensive usage in space and on space grade electronic components that have the ability to survive decades in space.

The investment of time and money is quite large as well. This is one of the critical reasons why there are only a select group of countries/developers for these satellite systems. While these large systems are complex and serve for more than a decade, it is necessary to take note of the rapid developments in technology within that decade. As a parallel, consider the development of the mobile phone industry from the end of the millennium in 2000 to the current smartphones available. The average smartphone today has several times the processing capability and storage of a satellite in past decades. Small satellites feed off these unprecedented rapid developments. Small satellites based on smartphones are already being tested by agencies such as NASA. The technology small satellites thrive on is essentially based on Moore's law. Professor Sir Martin Sweeting has demonstrated (Figure 1) that Moore's law is closely associated with small satellites, given the evident decrease in the Ground Sampling Distance (GSD) and increase in data rates and data volumes over the years. This corresponds with the decrease in the size of spacecrafts for several Earth Observation (EO) missions over the past decades.

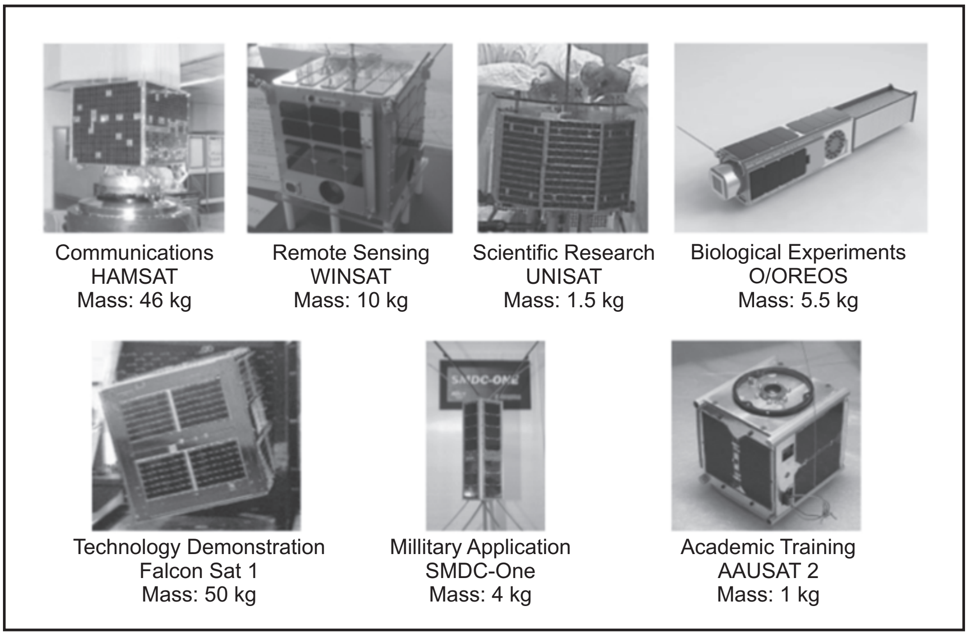
Figure 1: Moore's Law Implications for Small Satellites[4]





The distinct features of small satellites provide an opportunity to have smaller teams and encourage new actors to develop capabilities in the space domain. Small satellites encourage testing novel applications, methods and technologies such as open source hardware and software, formation flying, non-space grade hardware – which might not be under the purview of large-scale satellites. This remains the reason why small satellites have been considered a disruptive technology by numerous space mission experts. Small satellites have brought new players into the current space market, including universities, amateurs, developing countries, etc. Small satellite programmes are particularly attractive since they are affordable for several applications that are showcased in Figure 2. There is an observed increase in developing countries, groups from the academic world, small teams of space enthusiasts, etc, in developing their own space missions based on small satellites, some of them as entrepreneurial efforts for space based services, which are otherwise backed by governmental agencies. This study suggests a case for development of the small satellite ecosystem in India for the benefit of various end users within the country.

Figure 2: Applications of Small Satellites[5]



Small satellites have allowed several non-space countries that had previously been users of space applications and were dependent on a limited number of players in the space arena, to establish basic capacities in space technology as a step to becoming self-reliant. Thanks to the growing reliability of technology in commercial electronics, alongside the miniaturisation of the technology itself, increasingly capable small satellites can be developed with lower capital expenditure than before. This is allowing small institutions to take on such projects. Surveys of the technical feasibility of using small satellites have indicated that small satellite platforms are not limited to technology demonstration but can support missions to produce unprecedented data products with very high temporal resolutions, which can create value in science, defence as well as commercial applications.[6]

Following this trend, several university-based small satellite projects have arisen and led to the establishment of space enterprises that are now performing on a commercial basis across the globe. Small satellites have also been recognised by the United Nations Office of Outer Space Affairs (UNOOSA) and have found a special place under its Basic Space Technology Initiative (BSTI), which focuses on the development of affordable, small-satellite platforms with mass below 150 kg, and on their associated technical, managerial, regulatory and legal issues.[7]

2. Academic Small Satellite Missions

The 52 kg University of Surrey Satellite (UoSAT-1) was the first academic small satellite to be launched into orbit, in 1981. UoSAT-1 was built with a budget of GBP 250,000 in 30 months and was operational until it decayed eight years after its launch.[8] It was a proof of the concept of extended use of Commercial-Off-The-Shelf (COTS) technology in space. Following the success of COTS, many universities and non-governmental entities experimented with the approach. In 1999, collaboration between the California Polytechnic State University and Stanford University brought forth the CubeSat revolution in small satellites. The CubeSat standard essentially allowed further reduction of cost and development time while providing an opportunity to gain frequent access to space.[9] The first CubeSat was launched in 2003, and since then CubeSats have enabled hundreds of missions by its standardisation and reduction of costs and labour. The hallmark of small satellite programmes in global academia remains that of getting something into space even though there is a lack of dedicated space based programmes and personnel at universities.

The first university space mission in India came almost three decades after that of the world leader, at the time when the first Indian lunar exploration programme (Chandrayaan) was operational. Development of this first Indian academic satellite (ANUSAT) commenced in 2002. It was scheduled to launch in 2005,[10] but due to delays, the satellite was eventually launched in 2009. This first Indian university small satellite mission has reportedly spurred similar aspirations in 25 universities. ISRO supports academic missions by providing guidance to teams, infrastructural support, and training, alongside free launch service on-board its PSLV.[11] Following the first university satellite mission, four other small satellites were launched in a span of two years (Table 1). The CubeSat form factor also found following in India with STUDSAT and Jugnu adapting a 1U and 3U form factor for their missions. ISRO has extensively supported the small satellite missions in academia and has provisioned several participation options for universities which include:

- Design and development of the payload. The payload can even be accommodated on ISRO's on-going satellite projects. ISRO takes responsibility for operations and acquiring data off the payload, while universities are responsible for data product generation and study.

- Providing the design for a standard nano-satellite bus which is fabricated by the institute. The payload too will be designed and developed by the institute. ISRO can provision critical materials such as solar panels, batteries, multi-layer insulation, low emittance tape, kapton tape, thermistor, etc. Once the satellite has passed ISRO's reviews, the mission is considered for a launch as a piggyback.

- Complete design, development, fabrication and testing of the small satellite by the institute under the technical guidance of ISRO. Some of the mission critical components mentioned above can be provided by ISRO. Once the satellite has passed all necessary design and test reviews, it is considered for launch as a piggyback.[12]

Table 2 provides the list of on-going small satellite missions. Unfortunately, one of the distinct features of small satellite development at academic institutes in India has been the delays in delivering the satellite. For example, Pratham, the satellite from the Indian Institute of Technology, Bombay, was initiated in 2007 with a Memorandum of Understanding (MoU) between the institute and ISRO. Although the satellite team has reported a funding of Rs 1.5 crore (USD 250,000), the satellite has not been completed owing to lack of manpower, administrative delays and technical glitches.[13]

Table 1: List of University Small Satellites from India

Satellite	Mass [kg]	Launch Date	Payload	Remarks
ANUSAT[14]	40	20.04.2009	Store and forward (messages)	First Indian university mission
STUDSAT[15]	1	12.07.2010	Imager (90m)	First Indian pico-satellite
YouthSat[16]	92	20.04.2011	Radio beacon for ionospheric tomography Hyper spectral imager for airglow measurements Spectrometer for charged particle studies	Indo-Russian mini satellite
SRMSat[17]	10.9	12.10.2011	Spectrometer for global warming observation	First Indian nano-satellite
Jugnu[18]	3	12.10.2011	Indigenous camera for near infrared imaging GPS receiver for navigation MEMS based Inertial Measurement Unit	

One of the main hurdles in running academic space missions in India is the lack of a programmatic approach to the development of small satellites. Only a programmatic approach can resolve issues such as retaining manpower – at least those who worked as lead systems engineers. Most academic missions in India face this critical hurdle due to the lack of a policy of reasonable employment within the small satellite programme. While federal universities explore various avenues for funding including the MHRD, Corporate Social Responsibility (CSR) programmes of companies, alumni associations, etc., there is clearly a lack of a dedicated funding model. Although ISRO supports small satellites initiatives by providing consultation, materials, and launch support, these are essentially issues that emerge after the conception/identification of a funding model for small satellite missions.

Table 2: List of On-going University Small Satellites from India

Satellite	Payload	Mission
PISAT[19]	Gom Space Nano Cam	Technology Demonstration/Student Training
NIUSAT	Miniature Wide Field Sensor (MWiFS)	Agriculture and disaster management support
Parikshit[20]	De-orbiting using Electrodynamic Tether	Demonstration of De-orbiting Technology
	Thermal Imager	Cloud cover monitoring, urban heat islands mapping and ocean surface temperatures
Swayam[21]	Store and Forward	Half duplex communication over the HAM frequency band
SNSAT[22]	Spectrometer	Measurement of Greenhouse Gases between 900nm and 2.5?m (near infrared band)
IITM SAT[23]	High Particle Energy Detector	Earthquake prediction via measurement of high energy particles in the ionosphere
Pratham[24]	Spectrometer	Ionospheric Tomography via measurement of Total Electron Count
Azad-1[25]	Imager	Solar imaging
StudSat2[26]	80m CMOS Imager	Demonstration of Inter-Satellite Communication in a twin satellite configuration
Kalam[27]	Imager	Ecology of Chotanagpur plateau

In contrast, several other countries pursuing academic small satellite missions have identified a funding model for continued investments in research and development of small satellites. For example, the University of Tokyo has been granted a ¥4,105,000,000 (~USD $35.5 million) for the project 'Establishment of New Paradigm of Space Development and Utilisation with Nano-Satellites Introducing Japanese-Original Reasonably Reliable Systems Engineering'.[28] The programme focuses on technological innovation, strategy, and utilisation of nano-satellites via research and development, which is conducted through the coordinated efforts of many different universities, researchers and enterprises.[29] Similar grants have been given in Europe by the European Research Council (for example, a grant to University of Würzburg[30]) and in the United States with its National Science Foundation (~USD $10 million funding for 2008-2012).[31] In the current state of the Indian space programme, the interaction with academia is restricted to ISRO granting funds via the RESPOND programme created in the 1970s to involve academic institutes in research and development relevant to the country's space programme.[32]

The effects of sustained investments in space programmes elsewhere should be a lesson for India, more so with ISRO emerging as one of the premier space faring agencies of the world, producing many firsts in the arena of space science and technology. There is need for a programmatic approach within academia of the kind that has been extremely successful within ISRO since the 1960s. Only sustained investment can create state-of-the-art infrastructure for cutting edge research and development at the grassroots level. Moreover, long term investments not only create and retain manpower, infrastructure, but also provide secondary benefits, such as creation of social and commercial spin-offs. The intellectual property thus created can be exploited at both the local and the global level.

Table 3: List of SpinOff Companies from University Small Satellite Missions

Country	University	Spin-Off Company
United Kingdom	University of Surrey	Surrey Satellites Technologies Limited[33]
	Dundee University	STAR-Dundee[34]
USA	California Polytechnic State University	Tyvak Nano-Satellite Systems[35]
Netherlands	Technical University of Delft	Innovative Solutions In Space[36]
Denmark	Aalborg University	GomSpace[37]
Germany	Technical University of Berlin	Berlin Space Technologies[38]
South Africa	University of Stellenbosch	SunSpace& Information Systems[39]
Japan	University of Tokyo	Axel Space[40]

Table 3 provides a list of universities and their spin-off companies in the arena of small satellites in different parts of the world. A spin-off entity has the potential to employ university students who worked on small satellite projects, and can utilise their rich experience without any additional investment in them. Spin-off companies of small satellites are not as capital intensive as other space technology entrepreneurial segments due to the low-cost/mission and the smaller teams involved. The lack of an environment or an industry for small satellites in India forces graduates from Indian varsities with experience in developing small satellites to choose other allied fields or to pursue opportunities abroad, leading to brain drain from the country.

Spin-offs service several national and international needs which include supporting the civilian space programme, academic missions, exploring independent missions for unique data products, initiating technology transfer programmes for non-space countries/entities, developing e-commerce platforms for small satellites products and services, enabling dedicated missions for non-governmental users (including commercial entities), etc. The following are some examples:

- Surrey Satellite Technology has delivered over 40 missions and gone on to service space agencies which include the ESA, National Space Research and Development Agency of Nigeria, etc.[41]
- Berlin Space Technologies is currently running a comprehensive technology transfer programme for the National University of Singapore that will enable the latter to build micro-satellites.[42]
- GomSpace has developed a successful mission in collaboration with DSE Airport Solutions and Aalborg University to perform research and experimentation in space related to Software Defined Radio (SDR), with emphasis on receiving ADS-B signals from commercial aircraft over oceanic areas.[43]
- ISIS from Netherlands has launched the CubeSatShop, an online e-commerce platform for a broad range of products for cubesats and nano-satellites.[44]

All the universities involved in nurturing these spin-offs have had a programmatic approach with sustained investments. If such potential avenues are to be explored within India, there is need for an independent investment model backed by departments of the central government (for example, MHRD). This could well kick off a systematic investment approach to the country's academic blocks for sustained growth in state-of-the-art research and development whose benefits will be much more than just supporting the country's space programme.

3. Civilian Space Agency Small Satellite Missions

The first indigenously built Indian satellites Aryabhata and Bhaskara were experimental remote sensing satellites weighing 360 kg and 442 kg respectively. They were launched on board the C-1 Intercosmos from the Volvograd launch station in Russia.[45, 46] Subsequently, the country's mission to pursue development of an indigenous launch vehicle for satellites (Satellite Launch Vehicle-3), led to ISRO developing much smaller payloads which could be flown on the indigenous rockets. The 40 kg-class Rohini satellite series was developed. First success was achieved with Rohini (RS-1), after an initial launch vehicle failure to carry Rohini Technology Payload (RTP) into orbit.[47] These efforts continued with Rohini (RS-D1) and Rohini (RS-D2) for flights on-board the SLV-3. With the eventual development of bigger launch vehicles such as the Augmented Satellite Launch Vehicle (ASLV), ISRO took up the development of the ~150 kg-class Stretched Rohini Satellite Series (SROSS).[48] SROSS saw the development of four satellites, of which the last two (SROSS-C, SROSS-C2) were orbited successfully and provided scientific data.[49] These led the way to the development of state-of-art remote sensing satellites such as the Indian Remote Sensing (IRS) satellite programme.

ISRO's return to development of small satellites (less than 100 kg-class) was led by the development of HAMSAT, a 42.5 kg micro-satellite as India's contribution to the international community of Amateur Radio Operators (HAMs). HAMSAT was launched in 2005 as a piggyback along with the remote sensing satellite CARTOSAT-1.[50] The HAMSAT bus, however, was not a standardised bus for further missions based on the micro-satellite platform. Noticing the success of small satellite programs led by the University of Surrey/ Surrey Satellites Technology

Limited and the continued momentum in the development of small satellite missions by various countries including China, Israel, South Korea, and Sweden for various applications, ISRO embarked on the development of a 100-kg class satellite as a standardised bus.[51] The Indian Mini Satellite (IMS) satellite series was envisaged as a platform for carrying payloads for earth observation, space science research, atmospheric and ocean related studies. The stated objective was to develop advanced miniaturised technologies to achieve performance of IRS class satellites on the miniaturised platform.[52] The IMS-1 was launched in 2008. The development of IMS-1 led to further achievements in various aspects of the sub-system design and architecture of the satellite itself. Some of them were single system configurations without redundancy, miniaturisation of electronics including reaction wheels, magnetometers, star sensor, camera, etc.[53]

The IMS 100 kg-class bus was replicated again with YouthSat, launched in 2011 as a joint Indo-Russian mission.[54] Without a sustained roadmap for small satellites, the IMS-1 has seen no further replication or application in experimental/scientific missions. In contrast, counterparts of ISRO such as the French Space Agency (CNES) have initiated development of small satellites of micro-class (~100kg) and developed it into a sustained programme. CNES pursued the development of generic small satellites in a similar class of the IMS bus (100 kg, 500 kg variants) and flew the PROTEUS mini-satellite and the MYRIADE micro-satellite in 2001 and 2004 respectively.

The development of Myriade was taken up by CNES in 1998 to deliver missions that combine high mission performance with small volume/mass, while utilising the technology advances in miniaturisation.[55] (Table 4 provides a comparison of bus architecture of

IMS-1 and Myriade.) Myriade has turned into a low cost platform which provides frequent opportunities for micro-satellites as secondary payloads which can be flown at least twice a year. The development of the Myriade platform has led to several CNES participatory missions including the DEMENTER (detection and characterisation of electromagnetic waves signals), PARASOL (addressing climatology), MICROSCOPE (demonstration of equivalence principle), and PICARD (sun observation). Moreover, the technology and the platform have been used by the likes of commercial spacecraft manufacturers EADS/Astrium and Thales.[56] A total of 15 satellites have been built on the Myriade platform with CNES realising several scientific missions, while industry used it for its own needs. This is in sharp contrast to the shelved IMS-1 bus.

Small satellites are not only making a mark in the 100 kg-class but also in the nano-satellite/ cubesat class for their distinct ability to be platforms that can be rapidly developed and launched for experimenting with ground-breaking technologies in space in an efficient and cost effective manner. Gaining space heritage remains critical for any component/technology, and small satellites even in the nano-satellite class have been used by space agencies including NASA, ESA, JAXA, etc, in testing emerging technologies which may well find their way into their future space missions. Several of these agencies have also used small satellite platforms of the nano-satellite class as a testing ground for innovative science and engineering technologies on a smaller scale in the space environment and have gained an understanding of how some of the hardware implemented in these experimental missions perform/survive the radiation, temperature and vacuum conditions encountered in space.

Table 5 provides a list of nano-satellite missions undertaken by NASA. Apart from the science based payloads, the mission profiles of these spacecraft include biological tests, next generation propulsion systems and communication systems, modern de-orbiting technologies, new sensor performance assessment tools in space environment and tests on the ability of smartphone-based COTS to perform in space. Some of the missions under development such as the Edison Demonstration of Smallsat Networks (ESDN) constellation provide the opportunity to demonstrate swarm networking of spacecraft, which can be performed in a cost efficient manner with these small spacecraft. In response to the rapid growth in interest in small spacecraft for many types of missions in the Earth's orbit and beyond, NASA commissioned a study on assessing the state-of-the-art in small spacecraft (less than 180 kg) and released a detailed report. The report provides an overview of the current challenges in small spacecraft technology while also giving critical information about COTS components/technology that have performed successfully in space.[57]

A programmatic approach to small satellite missions thus has a multitude of payoffs that include:

- Opportunity to rapidly develop novel missions, including constellations, based on standardised bus architecture (e.g. 1U, 3U, 6U form factors) with a single launch. With this prospect, NASA, for example, has developed a Nano-satellite Launch Adapter System (NLAS) to increase access to space while simplifying the integration process of nano-satellites onto launch vehicles. The NLAS consists of an adapter, four dispensers and a sequencer providing an ability to carry up to 24 nano-satellite units as secondary payloads.[58]

- A chance to inexperienced space engineers to gain valuable experience in systems engineering with 'simpler' design, development, fabrication, testing and in-flight operations that are typically completed in a timescale of two years.
- While bigger spacecraft involve hundreds of engineers and scientists with a larger developmental timescale, costs, and extremely tight mission architectures, they do not encourage risk taking, which nano-satellite missions provide. In these spacecraft, the scope for invention to gain space heritage for a new payload/component/technology reduces considerably. With small satellites, the ability to gain 'faster' space heritage, for new components/technologies in future missions increases.
- Many of the nano-satellite missions are analogous to robotic missions – they conduct experiments in space without a dedicated cost intensive laboratory where human beings have to be present, such as the International Space Station. For example, the PharmaSat is a controlled environment micro-laboratory packed with sensors and optical systems that can detect the growth, density and health of yeast cells. The study is on how the yeast responds to an antifungal treatment and will provide inputs about drug action in space.[59] Thus tests in allied fields can also be conducted at these missions.
- The non-traditional (non-space grade) approach to design, development and testing together with the low capital costs allows independent development of COTS-based technologies by industry in support of these missions. On successful on-orbit demonstration (design to on-orbit testing takes typically about two years), this has the opportunity to go global since a standard for small spacecraft has been developed.

A dedicated programme on small satellites with a 'transparent' timescale and goals has benefited several space agencies across the globe and spurred interest in academia and industry to explore several mission avenues of research and commerce. ISRO is one of the premier space agencies that has successfully employed a programmatic approach to development of space systems over five decades and is a model for several new space countries to pursue a civilian programme with a definite impact on the common man. Without a dedicated roadmap in the small satellite programme, ISRO has not been able to continue and carry forward its initial momentum in the development and utilisation of small satellite platforms. There have been a limited number of missions that have enabled further miniaturisation and testing on-orbit of some of the modern technologies to bring down the overall size of the spacecraft while improving its performance. There is definite need to consider a roadmap for small satellites within the country to reap the benefits of such a dedicated programme.

Table 4: Comparison of IMS and Myriade Bus Architectures

Bus	IMS-1 of ISRO[60]	Myriade of CNES[61]
Physical Dimensions	0.604 x 0.980 x1.129 m	0.60 x 0.60 cm x 0.80 m
Mass	83kg	130kg
Design Life	2 years	2 years
Power Generation	Two deployable sun pointing solar panels generating 220 W power	Two deployable sun pointing solar panels generating 200 W power
Power Storage	105 Ah Lithium ion battery	14 Ah Lithium ion battery
Pointing Accuracy	±0.1º	< 0.02º (1?) each axis
Attitude Determination	Star Sensor, Miniature Sun Sensors, Magnetometers Gyros,	Sun sensors. Magnetometer, Star sensor, Gyros
Attitude Control	Miniature Micro Reaction Wheels, Magnetic Torquers, single 1 N Hydrazine Thruster	Magnetoactuators, Reaction wheels, Propulsion using hydrazine system
Data Storage	16 Gb Solid State Recorder	1 Gb
Payload Telemetry	10 Mbps on S Band	X Band - 18 Mbit/s to 80 Mbit/s
Payload Details	4-band multispectral camera with 36m resolution and swath of 151km	1.5-2.5 m Pan at nadir with swath of 17.5km (on AlSat-2)
	64-band hyperspectral camera with 550m resolution and swath of 128km	6-10 m MS at nadir (on AlSat-2)[62]
Launch Year	2008	2004

Table 5: List of NASA Nanosatellite Missions

Launch Date	Satellite	Payload/Mission Objective	Form Factor	Mass (Kg)
16/12/2006	GeneSat-1	Spaceflight affects the human body tested using bacteria[63]	3U	5
8/2/2008	NanoSail D	Demonstrate a deployment with some "sailing" capability by using only the solar radiation pressure onto the sail as a propulsion means[64]	3U	4
8/2/2008	PreSat	Spaceflight performance evaluation of generic biofluidic sample management and handling subsystem using optical detection[65]	3U	4
11/20/2010	O/OREOS	Organism/organic exposure to orbital stresses to study how exposure to space changes organic molecules and biology[66]	3U	5.5
1/17/2011	NANOSAIL-D-002	Demonstration of deployment of a compact solar sail boom system in space[67]	3U	4
4/21/2013	Alexander (PhoneSat 1a)	Supplements the capabilities of PhoneSat 1.0 by adding a two-way S-band radio to command the satellite from Earth[68]	1U	1
4/21/2013	Bell (PhoneSat 1c)	Demonstrate the use of Nexus S smartphone, the flight avionics for a small satellite[69]	1U	1
4/21/2013	Graham (PhoneSat 1b)		1U	1
11/20/2013	FireFly	Study the relationship between lightning and Terrestrial Gamma-ray Flashes which are sudden (transient) energetic bursts in the upper atmosphere[70]	3U	4
11/20/2013	PhoneSat 2.4	Demonstrating a smartphone can serve as an avionics controller & test a space-based communications system supported by the smartphone for potential future application[71]	1U	1
4/18/2014	PhoneSat 2.5		1U	1
4/18/2014	SporeSat	Investigate the effect of gravity on the reproductive spores of the fern, Ceratopterisrichardii[72]	3U	6
Under Development	Network & Operation Demonstration Satellite	Demonstrate new network capabilities critical to the operation of swarms of multiple spacecraft[73] [2 Satellites]	1.5U	2
	Edison Demonstration of Smallsat Networks	Develop technology to send multiple, advanced, yet affordable nanosatellites into space with cross-link communications[74] [8 Satellites]	1.5U	2
	EcAMSat	Investigate space microgravity effects on the antibiotic resistance of E. coli, a bacterial pathogen[75]	6U	15
	Optical Communications and Sensor Demonstration	Demonstrate optical communications system and low-cost sensors for proximity operations with cubesats and other spacecraft[76] [2 Satellites]	1.5U	3
	Integrated Solar Array and Reflectarray Antenna	Demonstrate a Ka-band reflectarray antenna that will increase downlink data rates for small spacecraft from the typical existing rates of about 10 kilobits per second (kbps) to over 100 megabits per second (Mbps)[77]	3U	5
	Cubesat Proximity Operations Demonstration	Demonstrate rendezvous, proximity operations and docking using two three-unit (3U) cubesats[78]	3U	5
	BioSentinel	Develop a biosensor to detect, measure, and correlate the impact of space radiation to living organisms over long durations beyond LEO[79]	6U	15

4. Industry Overview

Until the 1980s, the traditional space industry was built by players delivering turnkey solutions to different kinds of satellites (communications, remote sensing, etc.) where those commissioning/using these satellites (especially low earth orbit (LEO) satellites) have typically been governmental agencies. The barriers to entry for entrepreneurs in this segment have traditionally been the high financing risks alongside acquiring the capability to deliver complete end-to-end solutions. With the evolution of the small satellite industry driven by the success of commercial components in space, the economics of space have changed tremendously over the past three decades. Small satellites have substantially mitigated some of the risks (lengthy development time, large manpower and infrastructure, etc.) that are inherent while developing large missions and hence have spurred the growth of new space companies across the globe. Low capital expenditure, developmental and mission costs – being a distinct feature of small satellites – have encouraged new actors, which include universities, developing countries and commercial enterprises, and have created opportunities for several kinds of offerings within the small satellite space segment.

A market assessment by Space Works estimates that between 2014 and 2016, 56 percent of nano/micro-satellites shall emerge from commercial players while one-fourth of all the nano/micro-satellites launched in 2014 will be commercial of nature. The same study goes on to project 2,000 to 2,750 nano/micro-satellites between 2014 and 2020.[80] This growing interest in small satellites is also marked by the rise of suppliers of small satellite sub-systems, components and launch services.[81] Allied services such as ground station networks for downlinking of data from small satellite constellations and dedicated small satellite launchers built by private enterprises also mark the emergence of the small satellite industry. Based on the current demands of the market, the small satellite industry in the space segment can be mainly divided as follows:

- End-to-end turnkey solution providers
- Technology transfer programme providers for emerging space players
- Component/subsystem suppliers for small satellite missions
- Service/data providers using small satellites as platforms

Building on the success of commercial components and miniaturised microelectronics finding their way into space on-board small satellites, several new actors, many of them commercial companies, have showcased the ability of small satellites to deliver state-of-the-art data product on smaller platforms. Table 6 provides a market segmentation of several enterprises that offer the different product/service offerings mentioned above. In the past five years the commercial industry has gained momentum in providing services based on small satellites. Enterprises are now moving towards data analytics from remotely sensed data. Some of the recent applications have been in receiving AIS, ADS-B signals for vessel and aircraft traffic monitoring and imagery based data analytics solutions. Traditionally such missions were limited to governmental/security related users, but with companies such as SkyBox Imaging, Planet Labs, Spire and ExactEarth now delivering data in an unprecedented manner using swarms of small satellites, the user base of these data sets may well come down to individual levels. While many applications cannot forego high spatial, spectral and radiometric resolutions, several missions which demand fast change detection require high temporal frequency alongside frequent coverage. The ability to employ line based production techniques enables these companies to lower their capital expenses. Unlike traditional data providers (in EO/other), these companies now have the opportunity to use their large network of assets in space to improve their temporal frequency and coverage of the Earth. Essentially these corporate entities are now presenting the Earth as a large data set which can be monitored for changes using constellations. The complexity of building and launching satellites has been reduced to integrating missions, using a Ford production line approach to reduce capital expenditure.

The participation of commercial services built on small satellite platforms are led by US based SkyBox Imaging.[82] The USD 91 million venture backed data analytics company flew the world's smallest high resolution satellite (SkySat-1) in 2012.[83] The SkySat platform essentially uses the COTS approach to development of small satellites while pioneering a state-of-the-art imaging system to deliver 0.9 m PAN, 2 m multi-spectral and 1.1 m HD video up to 90 seconds from space.[84] This is proof that non-state actors can build a satellite imagery data product offering on a micro satellite platform that is almost comparable in spatial resolution to the CartoSat-2B (better than 1 m resolution) launched by ISRO in 2010.[85] Google acquired SkyBox Imaging for USD 500 million and currently updates its maps offering with the SkyBox assets in space.[86] Table 7 provides a comparison between the IMS-1 and SkySat-1. The latter uses only half the power while delivering a similar capability in pointing with a design life twice as good, and employs a communications and imaging system that is more than 20 times better (in Mb/s and resolution) at a cost that is only about 20 per cent higher. The difference between the two shows the leapfrogging of technology possible by investing in developing analytics platforms built on open source software tools, building miniaturised proprietary imaging systems and techniques and leveraging on commercial electronics while making them 20 times smaller than traditional missions.[87] Other services such as Automatic Identification of Ships (AIS) are now being explored on nano-satellite based platforms with companies such as Spire.[88]

India started investing in its space programme in the 1960s and has continued to do so for the past five decades. ISRO, spearheading the Indian space effort, expressed its willingness to establish technology transfer mechanisms during early 1980s, and allows licensing of know-how from various ISRO centres for commercial exploitation. The greater objectives are the facilitation of greater participation of Indian enterprises in various space missions, exploitation of applications in the commercial domain while deriving the benefits of spin-offs of such technologies.[89] Although the technology transfer programme has been implemented and has yielded results in vendor development for ISRO – enabling it to provision various products and services required in the Indian space programme including satellites, launch vehicles, communications, broadcasting, meteorological services and geospatial information services – the industry itself remains predominantly dependent on the sustained budgets allocated to the space programme to maintain operations. Moreover, unlike some the developed countries' space programmes, the Indian one has not seen the emergence of turnkey solutions providers for the space and launch segment. The lack of public-private partnership mechanisms in establishing such an environment may be one of the critical reasons why there are fundamental problems in the emergence of the space industry in India. There is a need to establish umbrella programmes which will allow the industry to emerge as an integrator and enable ISRO to play the role of a user/facilitator to users. Such models have been extremely successful in

Europe and America and have created an extremely competitive space industry that can cater to the requirements of other parts of the world. Although there has been an open call to industry to develop a high throughput communications satellite, the sheer amount of investment required in developing infrastructure and manpower, and the long timeline to fruition, pose hurdles in capital investment and risk to Indian enterprises.[90] Risk mitigating or sharing mechanisms that create confidence in the market may hence be a necessity in the current state of the Indian space programme to achieve turnkey solutions provider capability within the industry. Considering the current strength, opportunities and risks in the current organisation of the space programme, small satellites with their distinct features of smaller timescale, manpower, and infrastructure may provide an excellent starting point in developing turnkey solutions providers, while working towards building capability of integrating larger satellites.

Table 6: Small Satellite Industry Segmentation

Platform	Turn Key Solutions	Technology Transfer Programs	Component Suppliers	Service/Data Providers
Microsatellites	Dauria Aerospace	Surrey Space Technologies Limited	ATK	SkyBox Imaging
	ST Electronics	Berlin Space Technologies	Astro- und Feinwerktechnik	ExactEarth
	LuxSpace	Satrec Initiative	Space Micro	World Vu
	Sitatel		SSBV	
	SpaceBel		Microsat Systems Canada	
	Clyde Space		IntellliTech Microsystems	Planet Labs
	GomSpace		Blue Canyon Technologies	Spire
	ISIS		Aerojet	
	Tyvak		Tethers Unlimited	
Nanosatellites	Axel Space	N/A	New Space Systems	
	Pumpkin		Saber Astronautics	
	Sequoia Space			
	Astronautical Development			
	GAUSS			

Table 7: Comparison of IMS-1 and SkySat-1

Bus	IMS-1[91]	SkySat-1[92]
Physical Dimensions	60.4cm x 98 cm x112.9 cm	60 cm x 60 cm x 80 cm
Mass	83kg	83kg
Design Life	2 years	4 years
Power Generation	Two deployable sun pointing solar panels generating 220 W power	120W OAP (Orbit Average Power), use of body mounted solar panels
Pointing Accuracy	±0.1º	±0.1º
Data Storage	16 Gb Solid State Recorder	768 GB
Telemetry & Telecomm and Payload Details	10 Mbps on S Band	X-band downlink of payload data: 470 Mbit/s
	4-band multispectral camera with 36m resolution and swath of 151km	S-band uplink: 16 Kbit/s
		Pan (Panchromatic): 90 cm with a swath of 8km
	64-band hyperspectral camera with 550m resolution and swath of 128km	MS (multispectral): 2.0 m at nadir
		Pan Video up to 90 seconds @ 30fps with GSD of 1.1 m at nadir at FOV>2.0 km x 1.1 km
Launch Year	2008	2013
Cost	~$3.6 million USD[93]	~$5 million USD[94]

5. Defence Small Satellite Missions

Small satellites have gained popularity within defence establishments/defence related industry due to their unique capabilities which complement the operational capabilities of larger space systems. Some of the advantages of small satellites that defence establishments/industry are looking to take advantage of:

- The ability to provide coverage and support over very large geographic areas, to carry out over-the-horizon sensing and non-line-of-sight communications with improved temporal coverage.
- Due to the rapid response capabilities in constellation deployment, they can be considered for providing support from the preparation of deployment from the sensed increase of tensions, through the crisis and supporting full-scale operations. This may add a critical edge in supporting military operations across the full spectrum of conflict management.
- They can give rapid responsive support from space for operational control (e.g. ability of tactical commanders to directly to task satellites as their own assets) which shall play a progressively more important role in the future of warfare on land, on the sea, and in the air.
- The ability to reconstitute and quickly deploy/replenish critical space based operations after current assets turn redundant due to natural causes, or are damaged/destroyed during ascent or orbital destruction via ASAT.

The current ISRO imaging satellites which can be utilised by the armed forces include CartoSat series and the RISAT satellites. CartoSat-2A formed India's first dedicated military satellite mission (funded by the

Ministry of Defence) with an overall objective to provide scene-specific spot imagery in high resolution (GSD <1m) to the Indian armed forces.[95] CartoSat-2B has been launched as a follow-up optical imaging mission of CartoSat-2 and CartoSat-2A with similar resolutions. These two satellites form the backbone of high resolution imagery for the Indian armed forces. However, these satellites do not have all-weather capability and have a revisit time of four days.[96] The RISAT-1/2 complements the CartoSat satellites by providing it all-weather as well as day-night capability.[97] Although these satellites provide high resolution data, one of their main limitations is their temporal resolution. Small satellite platforms in the 100 kg platform (refer to SkySat-1) have recently achieved the same solution as the CartoSat series. Small satellites are an excellent means of bridging the gap in temporal resolution for a particular area of interest.

Table 8 provides a list of some of the small satellite based programmes pursued by defence establishments across the world. These are typical examples of the current use of nano/micro-satellite platforms for an array of applications including technology demonstration, responsive remote sensing, electronic intelligence (ELINT), space weather, etc. In the current organisation of the Indian armed forces establishment, there are no open sources indicating any specific division/programmes with end-to-end turnkey services that have a specific mandate on utilising outer space with a primary focus on security/military purposes. India's defence forces created an Integrated Space Cell in 2008 that has a mandate to utilise ISRO's space assets/capabilities for military purposes.[98] Due to the lack of an established space based defence programme in the country, the armed forces need to rely on ISRO, a civilian organisation with a clear mandate to exploit the civilian/societal benefits of outer space. Hence the possibilities of exploiting outer space for specific defence operations are limited to exploring the dual use of the civilian missions by the armed forces. Additionally, there could be active concerns within the international community if a civilian space agency goes into overdrive to support specific military programmes. India has typically separated its civilian rocket development (by ISRO) and military rocket development (by DRDO) and the same approach to satellite technology might benefit both the sectors.[99] Small satellites have gained some traction within the armed forces establishment in the backdrop of the Chinese anti-satellite (ASAT) tests. The tests have moved India's defence establishment to focus on the threat of ASAT and some defence establishment officials have proposed the idea of using a constellation of small satellites (of 30-60kg) with a payload as a warhead which can be activated in case of enemy attack to ensure the safety and security of Indian space assets.[100]

Alongside the ASAT related aspects of defence, the Technology Perspective and Capability Roadmap of the Headquarters Integrated Defence Staff, Ministry of Defence in part establishes the requirements of the armed forces. In terms of information dominance, the roadmap spells out the need for strategic forces to get real-time information in their areas of interest through satellites which produce sub metric resolution. The roadmap acknowledges the trend of miniaturisation of technology and points to the future trend of using small satellites in a network with the capability of working together to monitor moving targets on the ground or at sea anywhere in the world.

Other requirements are in communications, space weather, platforms with improved sensors, resolution and revisit schedules.[101] Another programme which is critical to the Indian coast line and in which small satellites can help is Automatic Identification of Ships (AIS). AIS via small satellites has been tried and tested over the last decade by countries such as Norway.[102]

A dedicated satellite programme within the armed forces will complement ISRO's satellites and offer the armed forces the option of integrating the dedicated military satellites into the services for specific operations/applications in a smoother manner. A dedicated military programme in satellites is also imperative for exploring areas such as space weather, ELINT, ASAT, etc, which are in the interest of the armed forces. They will also allow for a reduction in the length of the life cycle of space based military operations/services which typically need to move from experimental to operational phase. Such military service/operations may assume longer time-scales if pursued via ISRO which has the burden of delivering civilian services also. A dedicated programme is also imperative for data/operational security.

At present, the process from conception to delivery of satellite services requires exchange of information within civilian ranks. There is always a threat of misappropriation of information on systems/services. Small satellites with distinct features of low cost, length of timeline, etc, can be an excellent starting point for exploring some of the key technologies and services required by the armed forces. The increased capability of the armed forces in the launcher area can be utilised to augment the progress made in the launch vehicle programme of the armed forces to deliver military small satellites.

Table 8: Small Satellite based Defence Programmes/Experiments

Country	Agency	Satellite/Programme	Type	Purpose/Mission
China	Shanghai Engineering Center for Microsatellites/ Chinese Academy of Sciences (SECM/CAS)	CompanionSat (BX-1)	ASAT Capability	Test of some of the capabilities required for a co-orbital anti-satellite (ASAT) attack[103]
Singapore	Centre for Research in Satellite Technologies	XSat	Technology Demonstration	Demonstrate technology in support of high-resolution imaging capabilities and to analyse and implement on-board parallel processing algorithms, thereby demonstrating improved mission achievements for generally downlink-limited small satellite imaging missions[104]
Canada	Department of National Defence (DND), the Canadian Space Agency (CSA), exact Earth and COM DEV Ltd.	M3MSat (Maritime Monitoring and Messaging Microsatellite)	ELINT	Maritime surveillance of shipping traffic poses a considerable challenge to the Canadian forces[105]
France	French Defence Procurements Agency (DGA)	ELISA (Electronic Intelligence by Satellite)	ELINT	Prepare the ground for the future operational programme ROEM (Elint) for mapping the positions of radar and other transmitters throughout the world and determining their technical characteristics[106]
UK	Microsatellite Applications in Collaboration (MOSAIC)	TopSat (Tactical Optical Satellite)	Remote Sensing	Demonstrate that a micro-satellite can provide responsive high-resolution imaging, with 2.5 meter-resolution images delivered directly from the satellite to ground terminals within the same footprint[107]
USA	DARPA	Systems 6	Cluster Communication	Demonstration to divide the tasks performed by large satellites by assigning each task to a dedicated micro-satellite which would operate in clusters[108]
USA	U.S. Army Space and Missile Defense Command/Army Forces Strategic Command Technology Center	SMDC-ONE (Space & Missile Defense Command-Operational Nanosatellite Effect)	Military Communications	Demonstration of tactical BLOS (Beyond-Line-Of-Sight) communications[109]
USA	National Reconnaisance Office	Colony 1/2	Technology Demonstration	Demonstrate the feasibility of placing payloads on Cube Sats to accelerate technology evaluations, address under served missions, field capabilities with reduced cost, and tighten schedules relative to larger satellite acquisitions[110]
USA	DARPA	SEEME (Space Enabled Effects For Military Engagements)	Remote Sensing	Providing mobile individual war fighters access to on-demand, space-based tactical information in remote and beyond- line-of-sight conditions[111]
USA	Air Force	SENSE (Space Environmental NanoSatellite Experiment)	Space Weather	Space Environmental Monitoring (SEM) by advancing sensor miniaturization and by distributing sensors to provide expanded coverage[112]
USA	Naval Research Laboratory	ANDE (Atmospheric Neutral Density Experiment)	Space Weather	Provide total neutral density along the orbit (between ~ 400-100 km) for improved orbit determination of resident space objects[113]

6. Summary of Current Gaps and Recommendations

Small satellites gained traction in Indian academia more than a decade ago with the development of the first Indian academic satellite ANUSAT. Several universities have since shown interest in pursuing missions based on small satellite platforms. Several small satellite projects at universities have been delayed due to lack of integration into academic activities/curriculum, and absence of reasonable employment for graduating students who lead the projects. Universities therefore need to consider providing credits to students working on small satellite projects. There is need to embed practical education into academic grading which would encourage more students to join such projects.

Although ISRO supports small satellites initiatives in providing consultation, material and launch support, the main hurdles in running such academic missions in India is the lack of a programmatic approach to the development of small satellites. Sustained investments in small satellite programmes within the academic world have a proven track record of creating benefits, including state-of-the-art infrastructure for cutting edge research and development at the grassroots level in several countries. Such investments in academia have moved to the creation of social and commercial spin-offs which use the intellectual property created by these programmes at both the local and the global level. If such potential avenues are to be explored within the country, there is need for an independent funding mechanism through departments of the central government (such as the MHRD). This would lead to systematic investment in the country's academic blocks for a programmatic approach to small satellites in academia and is vital in creating sustained growth in space activity based on state-of-the-art research and development, whose benefits can go beyond just supporting the country's space programme. There is also need to encourage the development of space technology based SMEs which build on the IP generated in academic small satellite programmes. There is need not just for incubation/office support, but also for establishing a space systems laboratory that can work independently and is capable of delivering turnkey solutions. Such an initiative within academia with the support of the government will create an environment favourable for graduates from Indian varsities with experience in developing small satellites at university levels to apply their efforts for societal and industrial applications which can address several needs of the country, while limiting the brain drain from the country.

ISRO embarked on the development of small satellites with the Indian Mini Satellite (IMS) series. A 100-kg class satellite as a standardised bus was envisaged as a platform for carrying payloads for earth observation, space science research, atmospheric and ocean related studies. The overall stated objective was to develop advanced miniaturised technologies to achieve performance of IRS class satellites on the miniaturised platform. The first satellite in the series IMS-1 was launched in the year 2008. The bus has only found replication once with YouthSat. Without a sustained roadmap for small satellites, the IMS-1 has seen no further replication or application in experimental/scientific missions. In contrast, other counterparts of ISRO such as the French Space Agency have developed sustained programmes and as a result a platform such as the MYRIADE micro-satellite, first launched in 2004, has turned into a low cost platform which provides frequent opportunities for micro-satellites as secondary payloads which can be flown at least twice a year during launch opportunities. The Myriade platform has been successfully used in over 15 missions and has led the way to several CNES participatory missions for advancement of space science and technology. The platform technology has also been used by commercial spacecraft manufacturers. There is a need for a dedicated programme on small satellites in India with a 'transparent' timescale and goals that will spur interest in academia and industry to explore several mission avenues of both research and commercial nature. ISRO needs to employ a programmatic approach to the development of the small satellite programme to continue and carry forward its initial momentum in the development and utilisation of small satellite platforms. Although several tech transfer initiatives have been successful, the Indian space programme has not seen the emergence of turnkey solution providers. A roadmap for small satellites within the country to reap the benefits of such a dedicated programme, which has been demonstrated by agencies such as CNES and NASA, would also provide an opportunity to explore public-private partnership mechanisms in establishing an environment to provide turn-key solutions within the country at a smaller risk, timeline and cost.

The Indian space industry was established mainly through technology transfer mechanisms during the early 1980s, which enabled licensing of know-how from various ISRO centres for commercial exploitation. While ISRO calls for facilitation of greater participation of Indian enterprises in various space missions and exploitation of applications in the commercial domain while deriving benefits of spin-offs of such technologies, the Indian space programme has not seen the emergence of turnkey solution providers for the space or the launch segment. Although tech transfer initiatives have been in force for over 30 years, there is linearity in the market and heavy dependence on space agency budgets/specs etc. The lack of public-private partnership mechanisms in establishing such an environment to provide turnkey solutions may be one of the critical reasons for the inability so far of the space industry in

India to go global. There is need to establish such umbrella programmes which will allow industry to emerge as an integrator and allow ISRO to play the role of user/facilitator to mitigate risk and create confidence in the market and achieve turnkey solutions provider capability within the industry. Some typical examples of such programmes are Hodoyoshi in Japan and Myriade in France. Small satellites with their distinct features of smaller timescale, manpower and infrastructure provide an excellent starting point in developing a public-private partnership programme which can develop turnkey solutions providers who can over time achieve full capability of integrating larger satellites as well. Turnkey missions could allow independent development of technology in industry and provide an opportunity to compete globally and increase the reach of the Indian space industry.

Small satellites with their unique capabilities to provide coverage and support over very large geographic areas with improved temporal resolutions, rapid response capabilities in constellation deployment, continuous responsive support from space for operational control and the ability to reconstitute quickly and deploy/replenish critical space based operations have gained popularity within defence establishments across the globe.

Due to the lack of an established space based defence programme in the country, the armed forces need to rely on ISRO, a civilian organisation with a clear mandate to exploit the civilian/societal benefits of outer space. Distribution/separation of civilian space interests and military space interests has been in force in the launch programme, and the same in the space segment would provide an opportunity to quickly close the gaps in the space based needs of the armed forces. A dedicated programme on using small satellite platforms within the armed forces will allow the armed forces to explore the options of integrating the dedicated military satellites into the services for specific operations/applications in a smoother manner, while complementing the current services provided by ISRO satellites. Areas of military interest such as space weather, ELINT, ASAT, are typically on a parallel track with ISRO's civilian services mandate. Although ISRO has the capability to deliver these services for the armed forces, the timeline of such space based military operations/services which typically need to move from an experimental to an operational phase may be hindered due to the burden of delivering civilian services. A dedicated programme on space based military services/operations is therefore not only imperative for autonomy in rapid development and deployment of the armed forces but is also better for data and operational security. Small satellites can well be an excellent starting point for exploring some of the key technologies and services required by the armed forces.

7. Conclusion

Miniaturisation of technology and increased reliability of commercial components have greatly increased the possibilities of exploring outer space. The revolution in small satellite programmes across the world within academia, space agencies, industries and defence establishments are a distinct indicator of this. The proliferation of small satellite programmes is probably the only such initiative in the history of space exploration that has provided the opportunity to engage in outer space-related activities through end-to-end turnkey development at a cost, and within a time period that may not have been otherwise possible for several new actors including academia, emerging space countries, etc.

India has pursued steady investments in space activities which are fundamentally driven by public policy. This has created an ecosystem where ISRO has assumed responsibility for all space activities including launch of satellites, development of space systems and ground systems to cater to an array of users within the country. It is important to acknowledge the diversification of space activities within the country as well as globally and consider bringing about fundamental changes which will enable private industry to use ISRO's domestic base to relate to the global industry. Worldwide, spacecraft systems and utilisation of outer space has seen the emergence of non-state players in an unprecedented manner and the proliferation of space technology across borders, creating an independent value chain for users.

Small satellites with their distinct features of short time-lines, limited need of manpower, infrastructure, low material costs and risks, provide an excellent platform for testing within the current landscape of the Indian space sector. They have the potential to play a role in not only advancement of technology and catering to specific user requirements within the country, but also in policy issue related experiments including technology safeguards, IPR protection, government procurement policies, technical audit, risk management, international obligations and international collaboration, national security, permitting use of government owned specialised facilities like launch pads to provide launch services and financing options.

Ultimately, there is need for a national space policy that will provide clarity. It will entail a revised framework for Indian space activities which will be representative of the interests of academia, the civilian space agency, industry and the armed forces. Such a policy can provide leeway for developing specific programmes and funding mechanisms within the interest of these different islands of excellence and also allow carrying out space activities independently for faster and inclusive growth. These steps seem fundamentally important in creating a commercial ecosystem for space activities in India and could provide a foundation for companies to commit new investments to develop products or technologies, which shall not only provide for the local needs but can compete globally. The ripple effects of such an initiative may well include retaining highly skilled manpower within the country, reversal of the brain drain and a major step forward towards government initiatives such as Make in India.

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