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ABSTRACT

Small satellites have gained considerable importance in recent years. Although small spacecraft have existed for decades, their military applications have recently gained prominence owing to technological advances in their development and integration into the armed services of the major spacefaring countries across the world. This paper analyses the significance of small satellites in the C4ISR capabilities of the three service branches of the Indian military. Small satellites are not a panacea for the C4ISR needs of the Indian Army, Navy and Air Force, but will help partially address their sensor-related requirements. They also contribute to a multi-layered and distributed capability for the Indian armed services. Investment in Small Satellites should assume greater salience in Indian defence planning in the coming years.

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INTRODUCTION

To what extent can small satellites (SmSats) strengthen the Indian Armed Services' Command, Control, Computers Communications, and Intelligence, Surveillance and Reconnaissance (C4ISR) capabilities? This paper evaluates the integration between satellite communications, imagery and reconnaissance in the order of battle of the Indian Air Force (IAF), Indian Navy (IN), and Indian Army (IA). It does not undertake a comparative analysis of the Indian, Chinese and US armed services' space capabilities, but assesses the deficiencies in India's. The analysis uses emerging capabilities in these countries as a reference point by demonstrating the importance of SmSats for C4ISR missions. The IAF and the IN have dedicated large communication satellites for the execution of their missions. The IA, however, is yet to get its own communications satellite. All three Indian services benefit from an inventory of Earth Observation (EO) and Remote Sensing (RS) satellites. For the latter category of spacecraft and communications, SmSats based in low Earth orbit (LEO) could be useful, which the Indian armed services do not have at present. Satellites in Geostationary Orbit (GEO) are also advantageous because only three satellites are required to provide communications coverage for the entire globe. Their designs are simple since they do not require antennas to track their movement from the ground, allowing a single broadband high throughput satellite in Geosynchronous Orbit (GSO) to cover one-third of the planet.[1] Nevertheless, they are insufficient to meet all the communications and bandwidth needs of the Indian armed forces, which SmSats will help at least partially fill, and are vital to the conduct of modern air, ground and naval operations.

This report builds on previous publications by the Observer Research Foundation on how satellites help improve the Indian armed services C4ISR capabilities.[2] Although this paper draws on the report of the

National Institute of Advanced Studies (NIAS) on the utility of SmSats for national security and the armed services, it finds that the NIAS focuses too extensively on the Indian Space Research Organisation (ISRO), the primary developer and launcher of SmSats for the Indian military, and overlooks the growth of space startups in satellite and launch vehicle development.[3] The NIAS study also fails to adequately address the advantages and disadvantages of SmSats, and why a small constellation of large satellites are vulnerable and against whom. However, the NIAS report did conclude that "…production requirement (s)" should be shifted to "industry" or the private sector.[4] The emergence of space startups and the commercial space sector in India throws up some attractive possibilities for the country's armed services.

This analysis seeks to establish how SmSats are valuable by contributing to redundancy, expanding flexibility, survivability, and lowering costs for satellite launches and satellite operations. Redundancy gives you more options in the form of more sensor platforms, which SmSats provide. Redundancy can be built into satellites platforms such that if there were software glitches, ground control can rely on back-up systems that are built into the satellite. Redundancy comes in the form of numbers as well—the proliferation of SmSats to fall back on alternative capabilities when there are disruptions and access impediments to large satellites. The latter is harder to maintain and replace than SmSats, which have lower mass and cost less, thus contributing further to redundancy.[5] In addition, SmSats also provide flexibility by allowing military planners and decision-makers to switch to sensors from which to service their C4ISR needs. Finally, SmSats meet, in part, the survivability needs for war planners by expanding the number of targets the adversary must strike and destroy.

This report analysis, however, does not analyse the imperatives of active measures for attack against space-borne targets, and deterrence and defence of space assets with Kinetic Energy Weapons (KEWs), Directed Energy Weapons (DEWs), space-based weapons or through cyber and electronic media. It maps out the significance of SmSats in servicing the C4ISR needs of the Indian armed forces for terrestrial missions and operations. While there is some dispute over the merits of using the term "aerospace," which implies the air and space domains are "unitary,"[6] this paper uses the term because modern air, naval and ground combat operations are heavily invested and reliant on space assets (primarily satellites) for terrestrial military missions.

The SmSat revolution is widely considered consequential for communications, imagery, reconnaissance and surveillance. Adapting and imbuing flexibility in the country's space architecture should be high on the agenda of Indian strategic planners. Although this paper focuses on the C4ISR-related military applications of SmSats, they are not panaceas for the armed forces' space-borne C4ISR needs, nor are large satellites in high orbital belts dispensable.

While no space system is completely insulated from destruction, SmSats are easily replaceable at the end of their natural life or if destroyed as a result of military action from KEWs, DEWs, and cyber and electronic attacks.[7] Their development cycles are shorter and offer "responsive capability" for military contingencies.[8] A SmSat constellation that can be rapidly launched using a Small Satellite Launch Vehicle (SSLV) provides a measure of survivability by way of "surge" capacity, which generates a proliferation of space assets against the adversary's anti-satellite capabilities.[9]

The emergence of SmSats represents a significant technological shift as it is a result of developments outside the traditional aerospace sector. Generally, the mainstream aerospace sector has emphasised "...exquisite capability, long platform lifetimes and high-reliability components".[10] Breakthroughs in "software, processing power, data storage, camera technology, compressive technology and solar antennas efficiency" microelectronics occurred outside the aerospace sector.[11] Consequently, the developmental trajectories of SmSat technologies and traditional space programmes have been divergent. SmSats are the product of the innovation culture that drive technology startups.[12]

Since transmissions from satellites based in GEO and GSO suffer from very high latency or transmission time, creating a large constellation of SmSats in LEO as a supplementary (if not alternative) space borne C4ISR capability for the Indian armed forces is an attractive prospect (See Table 1). For instance, SpaceX, the American private technology company that is an active player in the commercial and civilian sector, launched a constellation of broadband high-speed internet satellites in LEO, despite apprehension that it might be unviable.[13] A similar conceptual approach and template is being considered for developing spacecraft for armed forces around the world using SmSat constellations in LEO to meet military communications, EO and RS necessities. Indeed, commercial space through lower launch and developmental costs has created opportunities for the armed forces worldwide.

Table 1: Comparison of systems using different satellite orbits

Satellite Type	LEO	MEO	GEO
Satellite Height km	500-1500	5000-12000	35800/36000
Orbital Period	95-115 min	3-7 hours	24 hours
# of satellites, coverage	40-800, global	8-20, global	3, no polar coverage
Satellite life (years)	3-7	10-15	15+
Handoff frequency	High	Low	None
Gateway cost	Very expensive	Expensive	Cheap
Doppler	High	Medium	Low
Round-trip propagation delay (UAV to control center and back via satellite	10-30 milliseconds (ms)	70-200 ms	0.5 s
Propagation path loss	Least	High	Highest

Source: N. Hosseini, H. Jamal, J. Haque, T. Magesacher and D. W. Matolak, "UAV Command and Control, Navigation and Surveillance: A Review of Potential 5G and Satellite Systems," 2019 IEEE Aerospace Conference, Big Sky, MT, USA, 2019, pp. 1-10

GLOBAL SMSAT AND SSLV DEVELOPMENTS: CHINA AND THE US

The global community is witnessing a unique change—the costs of launch and satellite development are on the decline even as national security threats are rising. This is a marked difference from the situation a mere 15 years ago. India too is facing a far more formidable space military actor—China— than it did two decades ago.

While there are trade-offs and limitations with any technology, an assessment of Chinese and American efforts in the SmSat and SSLV domain demonstrates the increasing significance both countries attach to these capabilities.

China already has a constellation of satellites as part of the Yaogan series, which is a network of electro-optical, imagery intelligence (IMINT), synthetic aperture radar (SAR) satellites and electronic intelligence satellites (ELINT). The Yaogan satellites operate within a 2000-km altitude, making them LEO-based spacecraft. They are not classified as SmSats since they weigh more than usual SmSats, but perform functions with reduced latency, high imagery resolution and low signal processing time due to their orbital trajectories and altitude. The ELINT batch of the Yaogan 9 series are placed in a 63-degree inclined orbit.[14] SmSat technology is significantly more superior now—and continues to improve—and there are several small spacecraft in LEO.

Microsatellites in 62- or 63-degree inclined orbits are able to identify the location and characteristics of radars and, when configured to coordinate with imaging satellites, can provide a comprehensive picture of the adversary's deployments and military movements.[15] For instance, the Yaogan 9 satellites, although not SmSats per se as defined in Table 1, operate in triplets, providing a good template for a larger constellation of SmSats. They move in a configuration that sequentially pinpoints the areas where electronic emissions emerge from surface vessels.[16] These satellites would be able to pinpoint, visualise and direct missile attacks against fixed Indian targets, such as air bases and advanced landing grounds.

Some consider satellites that weigh between 500-1000 kilograms as SmSats, as defined in Table 2. Under this classification, both subsets of the Yaogan spacecraft (9 and 2 series) would be considered as SmSats.[17] The Yaogan 9, 16, 17, 20, 25 and 31 clusters (consisting of three ELINT or remote sensing spacecraft at orbital inclinations of 63 degrees) should be of particular importance to the IN.[18] The Yaogan ELINT satellites are comparable to the US's National Ocean Surveillance System or NOSS.[19] Any three operational ELINT triplet constellations can make 18 contacts a day with a moving target,[20] and the target could remain outside the reach of these satellites for a maximum of 90 minutes. The Yaogan 2 series of reconnaissance and SAR satellites are also defined as SmSats, as per Table 2A, and are important for remote sensing. These satellites carry heavier instruments at roughly 98 degrees in in Sun-synchronous Orbit (SSO).[21] They are all LEO-based satellites.

Table 2[22]

Type of Small Satellites	Weight Class in kilograms
Minisatellite	100-180
Microsatellite	10-100
Nanosatellite	1-10
Picosatellite	0.01-1
Femtosatellite	0.001-0.01

Source: "What are SmallSats and CubeSats?", Science Instruments, National Aeronautics and Space Administration (NASA), 26 February 2019

Table 2A: Small Satellite Definitions

Under 180 Kilograms	NASA Small Space Craft Technology Program	The US Airforce Research Laboratory see classifies a SmSat to be between 50-100 kg.
Under 500 Kilograms	Euroconsult, global strategy consulting firm in the space sector	
Under 1000 Kilograms	Surrey Satellite Technology Limited (STTL) has higher weight benchmark	

Source: Bhavya Lal et al., "Global Trends in Small Satellites", IDA Science and Technology Policy Institute, July 2017, Washington D.C.

The Yaogan satellites are significant to the Chinese military's ability to maintain constant surveillance and track naval movements across the South China Sea, Western Pacific and Indian Ocean. They also allow Beijing to mount over-the-horizon strikes against surface vessels. There are several other areas of military concern for the People's Liberation Army (PLA), People's Liberation Army Navy (PLAN) and People's Liberation Army Air Force (PLAAF) beyond the South China Sea and Western Pacific—the Sino-Indian boundary, the Tibetan Autonomous Region and the Indian Ocean. The PLAAF has increasingly shifted to a robust and offensive posture capable of operating aircraft for a significant duration in the Tibetan Autonomous Region, which is adjoining to and contiguous with India.[23] A significant number of space startups in China are planned as LEO satellite constellations, providing remote sensing and communications to meet the C4ISR needs of the Chinese military.[24] China already operates several microsatellites, including the Shijian series.[25]

Chinese startups are also developing SSLVs, which will play an important part in launching SmSats by diversifying risk and reducing cost for the country's armed forces. China already has the Kuaizhou-1 (KZ-1) SSLV, which has three solid fuelled stages.[26] The KZ-1 is reserved for commercial and civilian SmSat launches. The China Aerospace Science and Technology Corporation (CASC) uses the Long March-11 to launch military payloads into LEO.[27] The KZ-1 launched on 11 May 2020—carrying two 93-kg satellites into LEO as part of the Xingyun narrowband constellation, with an L-band communication system and "unspecified" additional payloads on board—may have military applications.[28] An L-band communications systems is notably very effective in rainy conditions, albeit with reduced speed, when other communications frequencies such as Ka-band and Ku-band suffer acute attenuation or propagation loss.[29] The satellites were built by the

Xingyun Satellite Co., a subsidiary of CASC, which is known to launch satellite payloads for the Chinese military.[30] It is important to recognise that satellites launched ostensibly for civilian or commercial purposes can carry military payloads as well. Indeed, China appears to be in the middle of a SmSat expansion.

Private space technology startups are making a mark in China as well by developing micro and nano satellites.[31] The true extent of the relationship between private space startups and the Chinese military is unclear, but the private sector does contractual work with the military. The military seeks to leverage the innovative dynamism of private companies, which would be in keeping with Civil-Military Fusion (CMF) directive laid out by Chinese President Xi Jinping, which seeks to generate "synergies" between the commercial and defence sectors.[32] Several individuals who previously ran military-affiliated institutes currently run Chinese space startups,[33] including LinkSpace, i-Space (which develops medium-sized rockets), Zhuhai Orbita Aerospace Science and Technology, and Beijing Galaxy Space Internet Technology.[34] Chinese space unicorns are also supported by a significant amount of venture capital, but it would not be surprising if state funding found its way into some, if not all, Chinese startups and passed off as venture capital (See Table 3).[35]

Table 3: Chinese Space Startups[36]

Startup	Description of Major Activities
Expace	Only partially private, state-owned and known for space launch vehicles such as the Kuaizhou -1A. Plans to build larger rockets like the Kuaizhou-11 and Kuaizhou-21.
One Space	Beijing-based start-up known for launch vehicles. Built and launched a sub-orbital rocket OS-X. Final goal is to be a major launcher of SmSats for LEO missions. Wants to use solid fuel rockets, which is normally not used in SLVs.
i-Space	Another major start-up developing SSLVs known as Hyperbola-1 with solid fuel for LEO SmSat constellations. Successfully carried out a test by sending solid fuel rocket past the Karman Line that divides the earth's atmosphere and space. Can launch 600 pounds into LEO with its Hyperbola-1 rocket when the latter is ready.
Landspace	This Beijing-based start-up is developing will use methane in its fuel propellant mix in its Zhuque-2 (ZQ-2) rockets and claims will be more fuel-efficient.
Link Space	Has made a foray into designing and developing Reusable Space Launch Vehicles (RSLVs).
Spacety	Maker of SmSats launching its first batch of four satellites and conducted more than a dozen space-related experiments. Expects to launch over a hundred microsatellites and is developing a satellite constellation of 288 laser-based communications microsatellites for WiFi connectivity at a cost and speed as ground based internet connectivity.
Commsat	Beijing-based satellite manufacturers that expects to place 60 satellites in orbit fulfil real time data needs for heavy machinery and the logistics sector. The start-up plans to develop a network of 800 satellites to meet Industrial Internet of Things (IIOTs) to process Big Data expeditiously through space borne assets.

Source: "7 China Space Start-ups for Rockets, Satellites", Nanalyze.com, *21 August 2018*

Although the US launched the greatest number of SmSats between 2014 and 2019, China launched SmSats mainly with military and industrial applications.[37] Table 4 shows Chinese investment in the form of the XinWei SmSat communications constellation. Beijing certainly sees promise in SmSat constellations for military purposes. The CASC has announced that China will build a 300 SmSat constellation known as *Hongyan*, with a retired CASC rocket technologist emphatically stating that "The technology can be applied to multiple fields including civil and military use."[38] At the least, the Chinese are likely to embed military payloads in commercial or civilian LEO-based constellations.

Table 4: Small Satellite Constellation (2017-2025)

Communications Satellites	**Constellation by owner**	**Approximate constellation**	**Orbit Altitude (kilometers)**	**Projected Launch Provider**	**Projected Launcher**
	OneWeb	720	1.200	Arianespace, Virgin Galactic	Soyuz, LauncherOne
	XinWei	32			
	Boeing	2,956			
	SpaceX	4,400+			
	LeoSat (not a smallsat)	108			
	BitSat	24	Unknown		
	Sky and Space Global	200	500-800	ISRO	PSLV
Earth Observation Satellites	Planet	150-1000	420 and 475	ISRO, ISC Kosmotras, Orbital ATK, SpaceX, Rocket Lab	PSLV, Dnepr, Cygnus, Falcon 9, Electron
	Satellogic	300	500	Kosmotras	Dnepr
	Blacksky	60	690	TBD	TBD
	UrtheCast	16	620	TBD	TBD
	OmniEarth	18	680	TBD	TBD

	Astro Digital	30	600	TBD	TBD
	Hawkeye 360	21	550-650	TBD	TBD
	Planetary Resources	10	*Unknown*	SpaceX	Falcon 9
	PlanetiQ	18	800	ISRO	PSLV
	Spire	250	500	Arianespace, ISRO, SpaceX, Rocket Lab	Soyuz, PSLV, Falcon 9, Electron
	Hera Systems	39	*unknown*	TBD	TBD
	Total	**9,070+**	**420-1325**		

Source: Bhavya Lal et al., "Global Trends in Small Satellites", IDA Science and Technology Policy Institute, Washington D.C., July 2017.

Similarly, the US's moves also provide clues on its plans and acquisition of SmSats for military applications. The United States Air Force (USAF) previously built large satellites for practical purposes to capitalise on each launch, since it was expensive to get a launch vehicle, but this also made the satellites easy targets.[39] SmSats, on the other hand, provide greater in-orbit mobility and are not easy to destroy. The US Army's Space and Missile Defense Command/Army Forces Strategic Command's Nanosatellites Program is planning to develop a constellation of nanosatellites for communications.[40] The US Army is using commercial SmSats in LEO by embedding military payloads, which are expected to provide reconnaissance, communications and navigation related support for "...frontline tactical ground units."[41] To use SmSats for precision timing and navigation from LEO, the US Army is pursuing three programmes—Lonestar, Polaris and Gunsmoke. Gunsmoke, begun in 2018, is geared for testing, integrating and demonstrating support for the tactical missions of ground vehicles. Using military payloads on commercial satellites is part of the US Army's "space defence in-depth" architecture, which does not rely only on SmSats in LEO, but also other high-altitude platforms for multidomain operations.[42]

Commercial satellites have historically played a role in meeting the US military's communications needs, for instance, during the first 1991 Gulf War.[43] But these satellites were typically larger than the ones that exist today. The Ka-band, which is a high through put frequency, has a larger pipe that can send down more data from a satellite, and lends itself to miniaturisation and portability. Indeed a 6U CubeSat enables the downloading of 10 gigabytes of data during a 10-minute overhead pass.[44] This is the type of SmSat with a high Ka-band frequency that has been developed by Astro Digital, a Silicon Valley-based company, in collaboration with Norway's Kongsberg Satellite Technology (KSAT). Astro Digital's miniature Ka-band transmitter and receiver has integrated directed horn antennas and can support downlink data rates from 35 Mbps to 2.2 Gbps.[45] The company also plans to launch about 30 Earth Observation SmSats. Astro Digital's Corvus BC spacecraft is integrated with three image sensors that can execute multi-spectral imaging.[46] The sensors can generate three times the data volume downlinked to the ground as compared to a single colour or panchromatic image sensor.[47] The spacecraft needs only a single ground station to downlink high bandwidth data. Further, Ka-Band miniaturised transmission equipment is highly suited for CubeSats.[48] Ka-Band can be complemented with the X-band frequency payloads, which is generally used for high throughput missions[49] by militaries across the world. To be sure, high data transmission using X-Band frequencies on SmSat platforms is still a work in progress. X-band and Ka-Band are the highest frequency bands, generate the most data and their increasing use is underway through transmitters from CubeSats.[50] For example, the National Astronautics and Space Administration, X-Band CubeSat MarCo uses an X-Band transmitter. Software Defined Radio (SDR) technology has emerged as a very important tool to re-configure the software of small spacecraft by providing "...signal processing and tuning over a wide range of frequency bands" especially in CubeSats without having to modify the hardware.[51] SDRs also give re-programmable capabilities and CubeSats lend themselves to reprogramming due to their compact size and affordability.[52] In addition, Commercial Off-The Shelf SDRs are available for CubeSats.[53] SmSat X-Band will also help move away from traditional frequencies that are likely to be highly congested, and with the emergence of SmSat constellations even more so.[54] To be sure, the next benchmark for high data rate transmission is the Ka-band, the X-Band could also serve as complementary frequency when the former suffers attenuation due to rain and humidity, allowing operators to exploit satellites passes better through the latter.[55] Further, X-band transmitter and antenna size are too large for CubeSats relative to Ka-band transmitters for now[56], nevertheless in due course miniaturisation could resolve this issue.

All three US armed services rely on Viasat Link 16 encrypted radio frequency, designed and built to relay information from ground vehicles, ships and aircraft for line-of-sight operations. The Viasat Link 16 is being integrated and tested on LEO-based CubeSats designed and built by Blue Canyon Technologies to enable the US military to conduct beyond-visual-line-of-sight operations.[57] The US Navy is also developing nanosatellites for ultra-high frequency communications and the USAF is developing ground infrastructure to sustain SmSat deployment. For instance, the USAF has engaged private sector firms to reduce the cost of satellite sensors and the development of satellite constellations.[58] Silicon Valley majors such as Ball Aerospace and Microsoft are helping the USAF use cloud computing and data processing innovations from commercial space to manage SmSat constellations in LEO.[59]

A 2017 USAF study drew attention to the overlap between commercial and military space: "The private sector is moving towards significant reductions in the cost of launch and is on the path toward a proliferated constellation of small satellites for sensing, communications, and command and control (C2) in space. This creates significant potential for contributions to all five-core Air Force missions, as well as to the missions of the entire Joint and Combined Force in the near, mid, and long-term."[60] (See Table 5).

Table 5: Strategic Common Ground between Commercial and National Security Space (USAF)

Commercial Application	Military Application
Large LEO constellations for Communications	Global Dynamic C2, Strategic Integration
Large LEO constellations for Rem ote Sensing	ISR, Space Situational Awareness
Human Spaceflight (Reusable space access systems that provide very low-cost, much higher reliability, higher flight rates, and rapid turn-around)	Rapid Reconstitution, Rapid Global Mobility, Air & Space Superiority, Global Strike

Source: Fast Space: Leveraging Ultra Low Cost Space Access For 21st Century Challenges, 13 January, 2017, Air University, Maxwell AFB, Al.

This clearly elucidates the importance of SmSats for the world's major militaries. Indeed in 2017, General John Hyten, the current Vice-Chairman of the Joint Chiefs of Staff, noted the importance of transitioning from, "...exquisite [and expensive satellite systems to]...more resilient, more distributed capabilities...[Y]ou won't find any of those big exquisite, long-term satellites... [which make for]...large, fat, juicy targets."[61]

EXPLORING THE INDIAN ARMED SERVICES' SATELLITE-BORNE CAPABILITIES

As the Indian armed forces become a more networked and integrated fighting force reliant on space-borne sensors, SmSats will be crucial. A networked capability for air operations can also contribute to the effectiveness of air combat platforms as they increase in numbers in the coming years. The IN also sees space as critical to the conduct of naval operations. For instance, the IN's information warfare doctrine states that satellites provide sensor information through revisit rates over specific combat areas at sea and enable networked fleet operations.[62] This is precisely the space-borne C4ISR capabilities that SmSats offer to the IN. Given the importance the IN's information warfare doctrine places on satellite revisit rates, the Yaogan 9 series dedicated to ocean surveillance should be of particular interest to it since satellite revisit rates and continuous surveillance, reconnaissance and communications are key.[63]

The IA does not have a dedicated communication satellite, and remains an exception by not articulating a coherent doctrinal position on the use of space. This is evident from the IA's Land Warfare Doctrine released in 2018, which at best makes a fleeting mention about the importance of improving capabilities in the space domain as an area of non-contact warfare.[64] The latter involves operations through and from space, cyber, electronic media and across the electromagnetic spectrum. Despite the lack of importance attached to space assets in the IA's land warfare doctrine, there is an opportunity for the service to leverage space borne sensors and imagery for its warfighting needs. Indeed, the IA is likely to be a large consumer of satellite borne sensor capabilities relative to the other armed forces. However, the Joint Doctrine of the three services emphatically emphasises the importance satellite systems enabling precision stand-off attacks. Technology, as the Indian armed forces' joint doctrine argues, is a key element of modern military operations.[65]

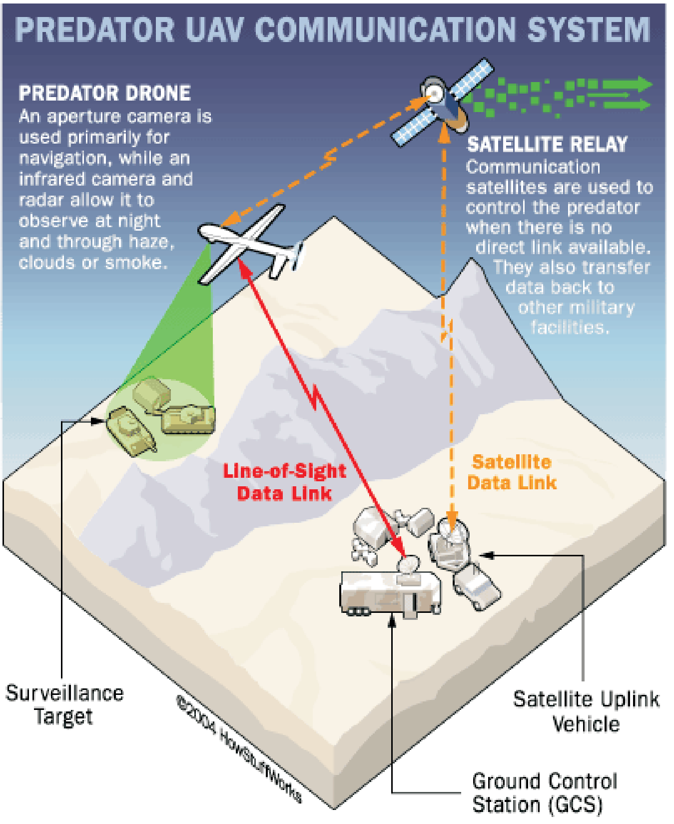
The use of space assets for communications, reconnaissance, imagery and geolocation are integral for airpower to deliver ordinance with lethality and precision. In any case, the PLAAF does consider air and space operations to be inseparable and central to the conduct of modern air warfare.[66] The IAF's doctrine also seeks to leverage space assets for air warfare and uses the unitary phrase "aerospace".[67]

Integrating space assets (satellites) with air operations is an imperative. The IAF sees space as a "complementary component" to air-related missions and operations.[68] The IAF wants to enhance its "sensor-to-shooter" capabilities by rapidly reducing the time it takes to detect, process information and respond to a threat. The IN and IA could also expand their SmSat capabilities to sustain carrier-borne air operations as well as Unmanned Aerial Vehicle (UAVs) missions and ground operations in mountain terrains, particularly against China's PLA. While heavy and large communications satellites are vital for space-to-ground, ground-to-air, air-to-air and space-to-sea contact, SmSats in LEO can also help the three services.

Availing data from SmSats may not currently be considered a pressing requirement, but it could become one in due course, particularly in wartime. The IA faces several challenges along the disputed boundary with China. Communications across and beyond the Sino-Indian border are difficult as the ground-based sensors allow 'line-of-sight' missions limiting the range of UAVs, but the acquisition of the Predator B or MQ-9 Reaper UAV will potentially change that constraint if the GSAT-7A satellite relay links with the Predator B drone.[69] for beyond-line-of-sight missions as illustrated in Picture A below.[70] As Ben

Schwartz of the United States-India Business Council observed in August 2019 regarding "India-specific drones," "weapons systems, the avionics suite, communications suite – they all need to be tailored to India's needs so it works with other equipment."[71] Currently, India uses Heron and the Searcher-II, the Israeli-built UAVs.

Picture A: Predator-Satellite Communications System



Source: Robert Valdes, "How the Predator UAV Works", howstuffworks.com*; Salman M. Al-Shehri, Pavel Loskot and Michael J. Hirsch, "Enabling Connectivity for Tactical Networks in mountainous areas by aerial relays,* Telecommunications Systems*, 71, 2019, pp. 561-575*

The IN will also benefit from the use of SmSats as ship-based sensors also limit UAVs to the line of sight. The GSAT-7 series of satellites meet India's current peacetime requirements. However, in wartime, they are likely to be vulnerable and easy targets.[72] The loss of large communications satellites will seriously impair military operations.

In 2010, India launched the Air Force Network (AFNet), which enables rapid digitised communication and data transmission against adversary threats with a high reliability and robustness. The AFNet connects the IAF's command and control centre, sensors such as the Airborne Early Warning and Control (AWACS) aircraft, and systems with shooters such as fighter jets and missile squadrons.[73] The launch of the AFNeT made the IAF the first among India's military services to establish a taut communications grid linking and integrating major air force installations, such as bases and the communications nodes, into a high bandwidth network.

Operationalising the AFNet was key to realising the IAF's goals of adaptability, availability and inter-operability.[74] Since the establishment of AFNet, the IAF has partially set up the automated Integrated Air Command and Control System (IACCS), which integrates all air and ground sensors.[75] IACCS was operationalised in Southern India in October 2019.[76] In 2018, the Modi government sanctioned INR 8000 crore for the integration of the radars under IAF, the IN, the IA and civilian air traffic control to provide unified air surveillance and reconnaissance.[77] As of today, the GSAT-7A provides the IAF with extended operational range and with appropriate adaptation helps link the satellite with airborne UAVs and surveillance aircraft.[78] In addition to the GSAT-7A both the AFNet and IACCS can be greatly bolstered with the SmSat bandwidth (for frequency bands see Table 6).

Table 6: Satellite Frequency Bands

Name of Band	Bandwidth in GHz	Functions and Capacities
L-Band	1-2 GHz	Carriers for GPS. Used in satellite mobile phones such as Iridium and Inmarsat provides communications at sea, air and land. Less susceptible to rain-fade, but low data rate.
S-Band	2-5 GHz	Weather radar. Surface Ship/Vessel radar. Also used in some communication satellites.
C-Band	4-8 GHz	Used in TV networks and broadcasts. Raw satellite feeds. Less susceptible to rain-related degradation as opposed to Ku-Band.
X-Band	8-12 GHz	Primarily used by the military. Continuous wave, polarization, dual polarization, SAR and phased arrays. The X-Bands frequency sub-bands are used for vessel tracking, air traffic control.
Ku-Band	12-18 GHz	Used for satellite communications.
Ka-Band	26-40 GHz	Used in communications satellites. Can provide uplinks in the 27.5 and 31 GHz. Provides high-resolution and close-range targeting radars on military aircraft.

Source: "Satellite Frequency Bands", European Space Agency.

In December 2018, the IAF's communication needs got an important boost with the launch of the GSAT-7A, a 2.2-tonne communications satellite with Ku-band transponders.[79] It allows the IAF to interconnect a variety of ground based radar stations, airbases and AWACS aircraft. The GSAT-7A, which is also known as the "Angry

Bird," has helped strengthen the IAF's drone operations by expanding communications links from ground-based stations to satellite connectivity with UAVs.[80]

For instance, the GSAT-7A will facilitate the effective exploitation of high altitude and long endurance by the Predator-B UAVS, which are satellite-controlled and their munitions satellite-guided, to strike targets at a distance (beyond visual line of sight).[81] The Predator-B uses a C-band line-of-sight data-link control system and Ku-band satellite communication for beyond visual line of sight in "persistent" ISR missions.[82] Large satellites such as the IntelSat EpicNG provide spot beam communications within 600 miles. If drones operate within the spot beam, they collect more data. Spot beams provide fewer possibilities for the adversary to jam communications between the satellite and the UAV, offer greater resiliency, and enable better data transfer and communications over a narrower and concentrated geographic area of operations.[83] SmSats have yet to fully and effectively demonstrate this capacity for communications for military drone operations. To that extent, large high throughput communications satellites in GEO will still matter for satellite-drone communications. Nevertheless, a sizeable constellation of SmSats could potentially meet the requirements of spacecraft-drone communications as spacecraft revisit and passes will be high. In any case UAVs, especially the Predator B, that India is acquiring rely on Ku-Band frequency for communications from GEO-based communications satellites and this frequency is increasingly becoming congested.[84] Consequently, SmSats in due course will increasingly meet the communications requirements of the Predator type UAVs.

Although the USAF uses SmSats for several purposes, only C2, strategic integration, ISR, Space Situational Awareness and rapid reconstitution are applicable to the IAF (See Table 5). Integrated missions involving all service branches are important to the Indian armed forces, and they are currently moving towards joint operations and missions. The enhanced abilities of sensing, communications and C2 from SmSats in space will be crucial for the IAF as the armed services integrate their operations.

Data transmission from the GSAT-7A satellite could be integrated with satellite relay communication following the acquisition of the Predator-B. (See Figure 1 for satellite frequencies).

Satellites such as the GSAT-11 have Ku- and Ka-band transponders. Ka-band transponders are more advantageous as their commercial and military bands can be co-located, enabling seamless complementarity.[85] Although the GSAT-11 can potentially meet military and commercial bandwidth requirements, other satellites, as is the case with Inmarsat-5 with its high capacity payload, can provide substantial bandwidth with its Ka-band frequency. However, rain and humidity impact the Ka-band frequency by generating signal loss.[86] Nevertheless, Ka-band is a high bandwidth frequency that can be especially useful to the Indian armed services. CubeSats such as the KSAT are also capable of generating high volumes of data through the Ka-band frequency.

The real test for the IA, IN and IAF is in developing and using SmSats to deliver Ka-band and Ku-band communications, voice communications and jam-resistant relays from LEO. In addition to position, navigation and timing (PNT) and persistent ISR mission capabilities at the tactical level, LEO-based SmSats will provide the armed services with greater battlespace awareness and enable more integrated operations. The IA must consider the US Army's use of nanosatellites for communications and PNT-related SmSats to sustain persistent ISR-related missions, which are determined by India's extensive land frontiers and disputed boundaries.

In addition to the heavy communications satellites, India fields a constellation of navigation satellites called the Indian Regional Navigation Satellite System, or NavIC. The constellation has eight operational satellites with three in GEO and five in GSO at a 29-degree equatorial plane.[87] While these spacecraft are necessary, they need to be supplemented with SmSats in LEO, and with payloads integrated in commercial SmSat constellations.

Weaknesses in sensor capabilities are a major challenge for the Indian armed services, and greater national focus will be needed on the potential that SmSats hold for modern warfare. Although the GSAT-7A-type satellites have greater bandwidth and transponder capacity, they are vulnerable to potential destruction given their limited numbers and large size. Thus, even though the instrument and transponder capacity of SmSats in LEO are limited, their relative survivability (and lower costs to replace) is what make them crucial.

Finally, following operationalisation, the armed services can avail the ISRO-developed three-staged SSLV for low cost and rapid launches to meet commercial SmSat needs and service military requirements.[88] This SSLV is capable of carrying a 500-kg payload to LEO and a 300-kg to SSO. The SSLV can carry a single payload as well as nano and micro satellites as part of a rideshare arrangement.[89] A robust C4ISR capacity for potent networked air operations, ground and naval missions using space-based sensors in LEO are as significant as a few large and heavy high-throughput satellites in GEO.

THE ROLE OF SMSATS

Large satellites are attractive in an uncongested and non-hostile space environment, but India's current strategic environment is far removed from this. While large communications satellites have some advantages, their numbers are so low that space-faring countries with complex national security threats, such as India, also require redundant space-borne sensor systems. SmSats and the SSLVs hold great promise as the costs for development of the former and the costs of launch of the latter have declined.[90]

Large communication satellites for military applications have several drawbacks. First, is the cost. GSAT-type communications satellites are expensive, and only extremely well-financed space programmes can sustain them.[91]

Second is that internet-related and communication transmission most often occur from large broadband and heavy communications satellites in GEO or GSO. In the absence of fibre-optic or cable-based connectivity, satellites in GEO or GSO are generally the source of communication connectivity. But the signal has to travel through thousands of miles of space and return, resulting in transmission delay, or latency, which can impact military operations.[92] Latency should not be interpreted as merely a "finite" term in the form of radio waves and signals travelling from space to Earth and Earth to space;[93] the term is expansive, covering the processing time of signals in devices—satellites and ground-based terminals—that are built on software and hardware.[94] These elements account for a delay in satellite transmission. So although it may appear that it takes little to no time for radio signals to travel from GEO to Earth, this is not the case (See Table 2A).

Table 7: Comparison of systems using different satellite orbits

Satellite Type	**LEO**	**MEO**	**GEO**
Satellite Height km	500-1500	5000-12000	35800/36000
Orbital Period	95-115 min	3-7 hours	24 hours
# of satellites, coverage	40-800, global	8-20, global	3, no polar coverage
Satellite life (years)	3-7	10-15	15+
Handoff frequency	High	Low	None
Gateway cost	Very expensive	Expensive	Cheap
Doppler	High	Medium	Low
Round-trip propagation delay (UAV to control center and back via satellite	10-30 milliseconds (ms)	70-200 ms	0.5 s
Propagation path loss	Least	High	Highest

Source: N. Hosseini, H. Jamal, J. Haque, T. Magesacher and D. W. Matolak, "UAV Command and Control, Navigation and Surveillance: A Review of Potential 5G and Satellite Systems," 2019 IEEE Aerospace Conference, Big Sky, MT, USA, 2019, pp. 1-10

Even in the context of military operations that must be conducted at high tempo, this latency delay might not be consequential, however, LEO-based SmSats do provide some insurance in case there are other disruptions. Therefore, LEO-based SmSats are as important as GEO-based satellites, because they lower latency. Furthermore, size, weight and power issues that constrained the dependence on SmSats in the past have been addressed in recent years, and there are ongoing efforts to overcome any remaining obstacles.

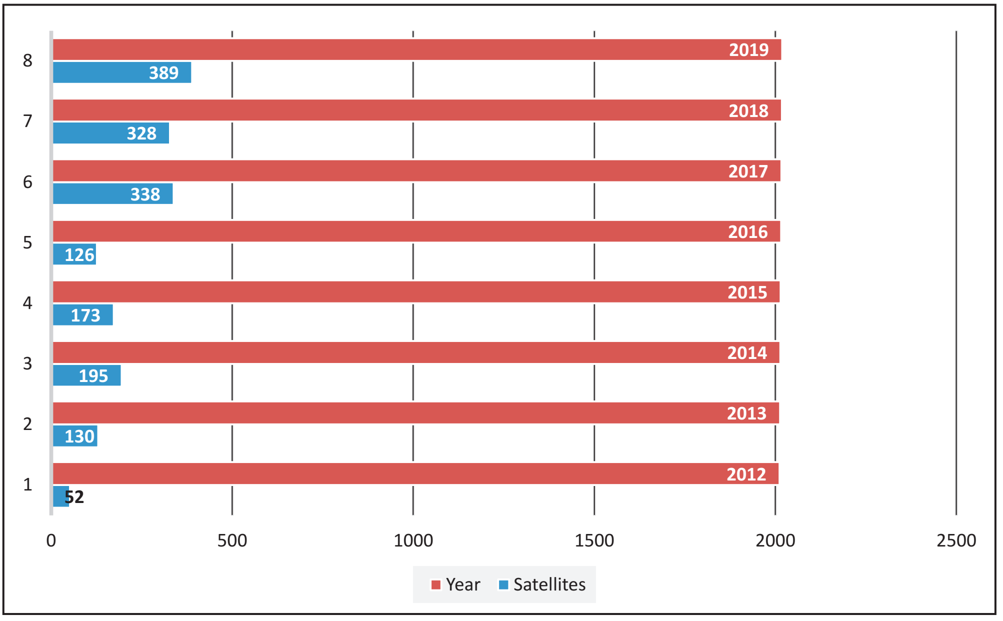
In recent years, SmSats have seen significant growth and help address some of the latency problems associated with large satellites in GEO. SmSats can be of five kinds—minisatellite, microsatellite, nanosatellite, picosatellite and femtosatellite— which are deployed in LEO (See Table 1). However, several satellites, such as some of China's Yaogan series, can also be termed as SmSats under other definitions. The ISRO has developed and launched its own SmSats, such as the Indian Mini Satellite-1 and 2, Youthsat and Saral,[95] and has launched several small satellites for domestic and foreign customers. India operates a dedicated electronic intelligence satellite to detect emissions across the electromagnetic spectrum, such as the EMISAT (weighing 436 kg),[96] and also operates the CARTOSAT-2 EO satellite series (weighing under 750 kg), which could be classified as a SmSat (See Table 2A).[97] SmSats, irrespective of whether they are commercial, military or scientific, are concentrated in LEO.

The acquisition priorities for space programmes that operate on a tight budget, such as India's, must include SmSats to meet the needs of the defence services and national security. India currently lacks a dedicated constellation of SmSats.

The SmSat is among the most significant spacecraft for military applications.[98] Microsatellites, which are geared towards collecting signals intelligence, are particularly appropriate.[99] The GSAT-7A-type satellites, although important, cannot be the sole source of space-borne sensor information, a role that must be supplemented by SmSats. SmSats can provide critical substitutes when military satellites, or the numerically smaller yet physically larger and more expensive satellites, operating in high orbital belts become non-functional due to destruction or suffer disruptions in wartime.

SmSat launches grew almost 7.5 times over the 2012-19 period (See Figure 1), revealing its growing significance for civilian and commercial applications, and potential for integration into national military architectures.

Figure 1: Small Satellites Launches - 2012-2019 (0.1-600 kilograms)



Source: "Small Sats by the Numbers: 2020", Bryce Space and Technology, *2020,*

The emergence of a slew of private technology startups provide opportunities for the Indian armed services to leverage SmSats for ISR from LEO. Private capital and monetary backing from the IA, IAF and IN will be needed to bolster the efforts of Indian space startups to develop SmSats. Bellatrix Aerospace, Dhruva Space, Kawa Space, AgniKul Cosmos and Astrogate Labs are some of the major Indian space startups (See Table 8), and their areas of work range from electro-optical and communications satellite systems to launch vehicle technology,[100] while also focusing on innovation and lowering costs for space access. In addition, the Indian Institutes of Technology, the Indian Institute of Science, and the ISRO's open attitude has helped "incubate" and encourage the involvement of unicorns in the development of SmSat space technology.[101] Further, the recent announcement by Finance Minister Nirmala Sitharaman levels the playing field between private sector entities and the ISRO, and will likely spur competition to achieve greater levels innovation in SmSat development, which the armed services can exploit to meet their C4ISR needs.[102] The Indian military leadership, with government directives and authorisation, should engage with these space technology startups.

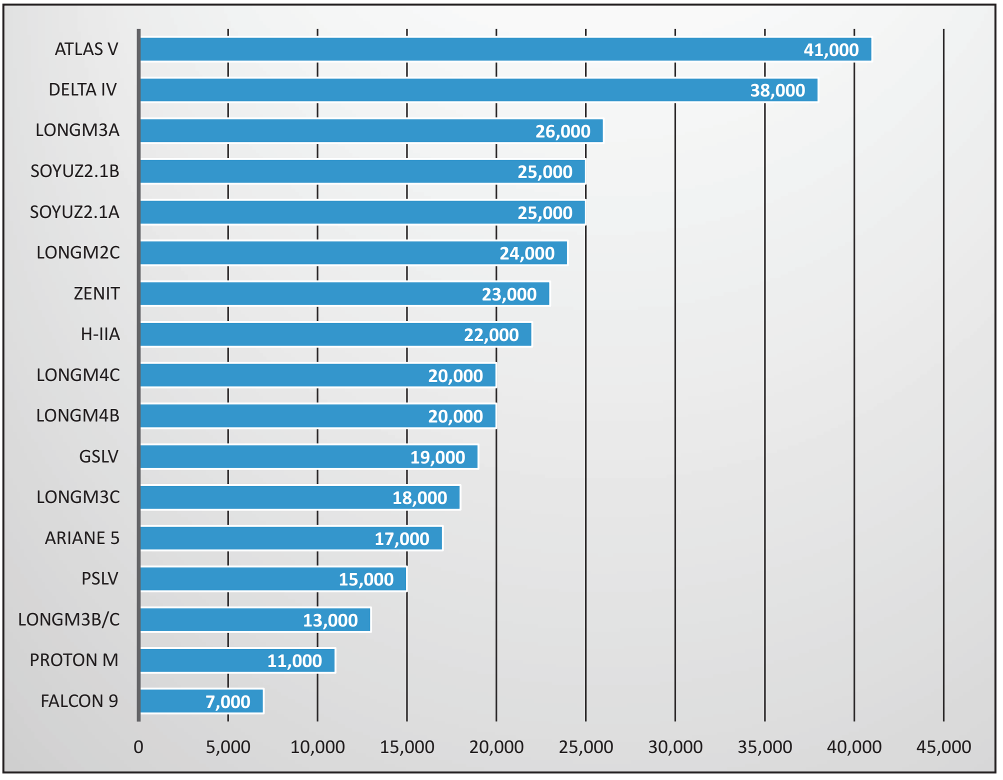
Table 8: Major Indian Space Start-ups

Start-up	**Description of Activities**
Bellatrix Aerospace	Developing SLVs using electric and non - toxic chemical thrusters
Kawa Space	Develops and operates earth observation satellites.
Dhruva Space	Varied applications. Provider of space infrastructure as service.
AgniKul Cosmos	Designs and develops launch vehicles for LEO missions.
Astrogate Labs	Makes optical communications systems for space applications.

Source: Sindhu Hariharan, "Demand for Small Satellites send Indian Startups into Orbit", Times of India, 6 October 2019

The development and operationalisation of the SSLV by the ISRO will reduce the cost of launching SmSats and consequently bring down the costs of LEO missions.[103] The Polar Satellite Launch Vehicle (PSLV) is too large and expensive to launch SmSats of any frequency; SSLVs will prove more economical.[104] Although competitive against most other launchers, the PSLVs payload carrying capacities are limited compared to the Falcon 9 or the Ariane, and the PSLVs and Geosynchronous Satellite Launch Vehicles (GSLVs) are not economical for geostationary transfer orbit missions compared to the Longmarch 3B/C or the Proton M, let alone the Falcon 9 (See Figure 2). Further, some Indian space technology unicorns will contribute to the development of their own SSLVs, thereby bringing down launch costs.

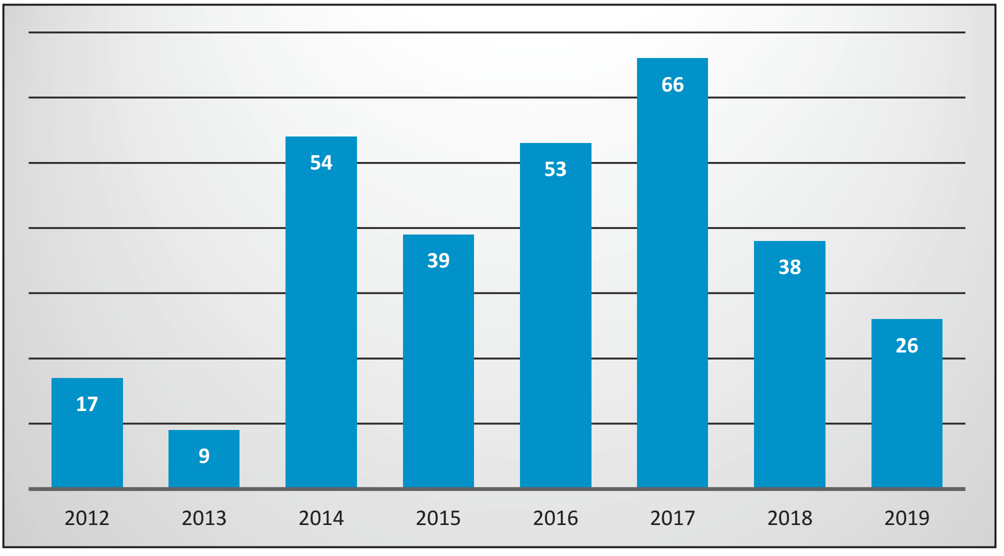
Figure 2: Cost per Kilogram in USD of Satellite Launches to GTO



Source: Adapted from "The Annual Compendium of Commercial Space Transportation: 2018", US Federal Aviation Association; and Andre Tartar and Tue Qiu, "The New Rockets Racing to Make Space Affordable", Bloomberg.com, *26 July, 2018, https://www.bloomberg.com/graphics/2018-rocket-cost/*

LEO-based SmSats can also help the IAF strengthen the networking and communications capacities of the AFNet and IACCS. The IAF was the first service to interlink all major ground installations with a high bandwidth network (through the AFNet). The GSAT-7A provides higher bandwidth for the AFNet. The IACCS links ground nodes with air borne sensors, the in-service GSAT-7A's space-borne sensors, and the air defence and C2 nodes.[105] The IA utilises about 30 percent of the GSAT-7A's capacity to meet its communications requirements.[106] The IN can also rely on external SmSat sensors for its maritime operations beyond the UAVs and heavy GSAT-7 communications satellite. Communications throughput for SmSats, which were historically low, have improved. The launch of SpaceX's Starlink satellite systems to overcome dependence on fibre optic cables for internet connectivity is an important development.[107] SmSats such as nanosatellites and CubeSats are most useful for remote sensing and Earth observation,[108] as well as satellite communications (for instance, KSAT). Remote Sensing satellites have seen a substantial increase globally since 2012, despite a slump in 2019 (See Figure 3). The IN will need a LEO-based SmSat constellation for near continuous ocean surveillance, detection of emissions, reconnaissance and for sustained revisit rates consistent with its information warfare doctrine. Remote sensing satellites will be crucial in this regard.

Figure 3: Percent of Remote Sensing Satellites Launched Globally



Source: "Small Sats by the Numbers: 2020", Bryce Space and Technology, Bryce Space and Technology, *2020*

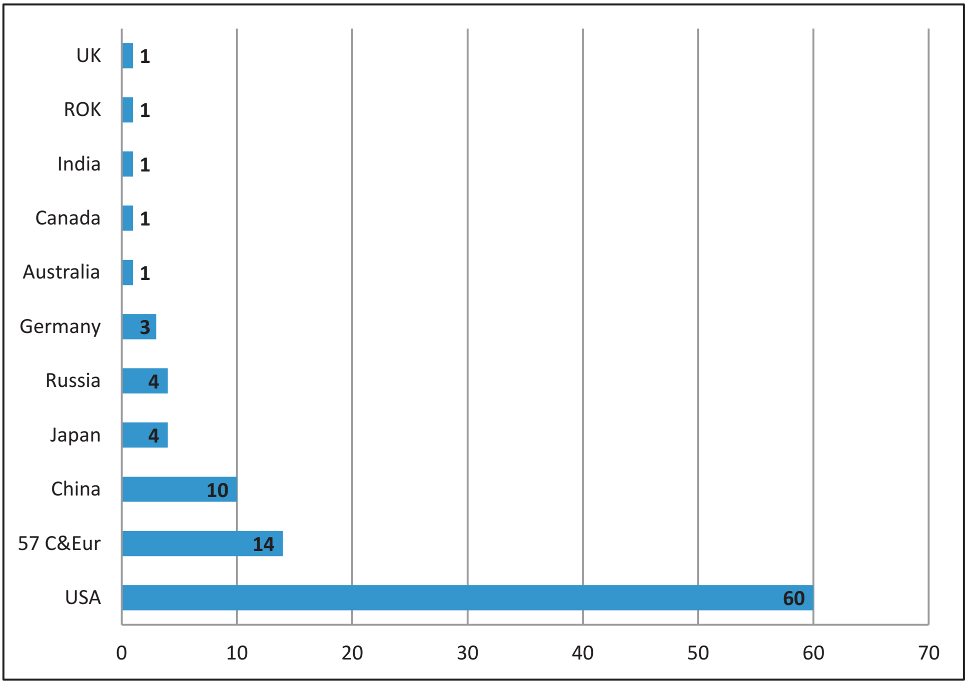
LEO-based SmSats are close to the Earth's surface, enabling them to pick-up surface-based electronic emissions more effectively and accurately that GEO satellites do. They also provide higher resolution imagery and focused ISR mission requirements within a narrow geographic area. The wide swath of GEO satellites is inadequate for

IMINT and ELINT related tasks, and their coverage at the poles is limited. LEO constellations, on the other hand, can provide persistent ISR coverage.

SmSats are useful and necessary for the Indian armed services as they can supplement existing in-orbit satellites. The armed services, and IA in particular, lack sufficient ISR capacity. Indian Chief of Defence Staff General Bipin Rawat's suggestion that the IN should deploy maritime aerial surveillance assets to perform ISR related tasks and missions on India's northern borders is at best a short-term solution.[109] Drawing on the IN's surveillance assets cannot be sustained in the long term. If anything, many of the tasks performed by the IN's maritime surveillance aircraft, such as the P8-I Poseidon, can be done with the help of LEO-based SmSats. Indeed, General Rawat's statement is both revealing and instructive—it is an unintentional yet implicit admission that the IA faces a shortfall in space-borne assets for persistent ISR missions and tasks along the country's northern and western land borders. What the Indian armed services lack is an in-depth space architecture, and this must be articulated as part of the tri-service doctrine.

GSAT-7A-type satellites and the recently launched GSAT-30 communications satellite[110] offer fat targets for the PLA Strategic Support Force and PLAAF. China has a slew of capabilities, ranging from the kinetic to the non-kinetic, to destroy heavy communications satellites in GSO.[111] A careful glance at other countries' efforts, particularly US and China, to develop SmSats for military missions could serve as a template for a more distributed space architecture for the Indian armed services. However, developing India's SmSat sector faces several challenges (See Figure 4); India only operates 1 percent of the world's SmSats, while China runs 10 percent and the US controls 60 percent.

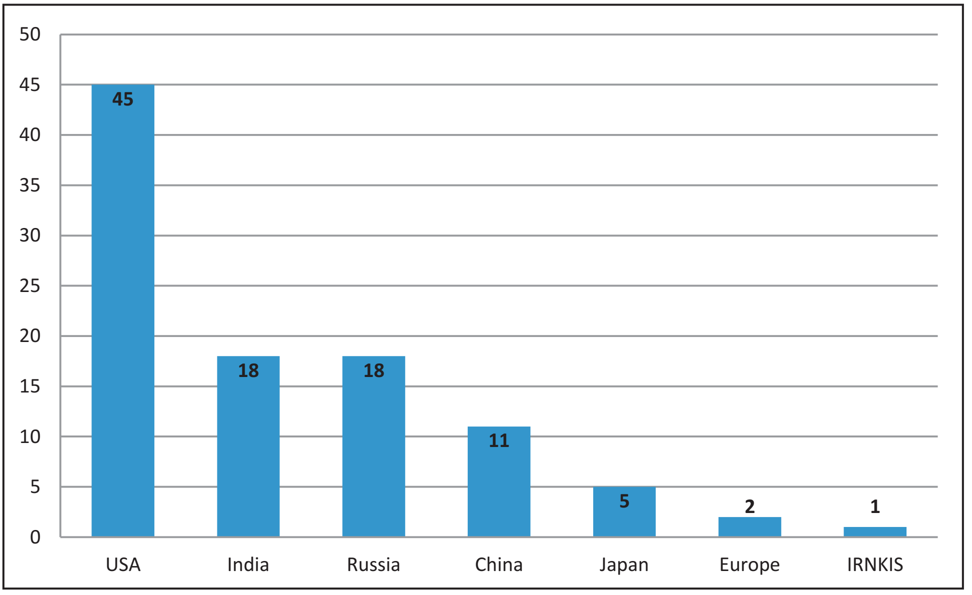
Figure 4: Percentage of Small SmSats By Operating Country - 2019



Source: "Small Sats by the Numbers: 2020", Bryce Space and Technology, Bryce Space and Technology, *2020*

India performs better in SmSat launches at 18 percent, second only to the US at 45 percent, on par with Russia, and ahead of China by seven percentage points (See Figure 5). However, India launched only nine government-owned satellites (including defence application spacecraft) in the 2012-2019 period, and has six times fewer satellites in orbit than China (See Figure 6). Figure 5 should be read in conjunction with Table-9, which gives data, if not for India specifically, but the USA, China and Russia, which operate the largest number of dedicated military satellites.

Figure 5: Percentage of SmSats by Country of Launch Provider



Source: "Small Sats by the Numbers: 2020", Bryce Space and Technology, Bryce Space and Technology, *2020*

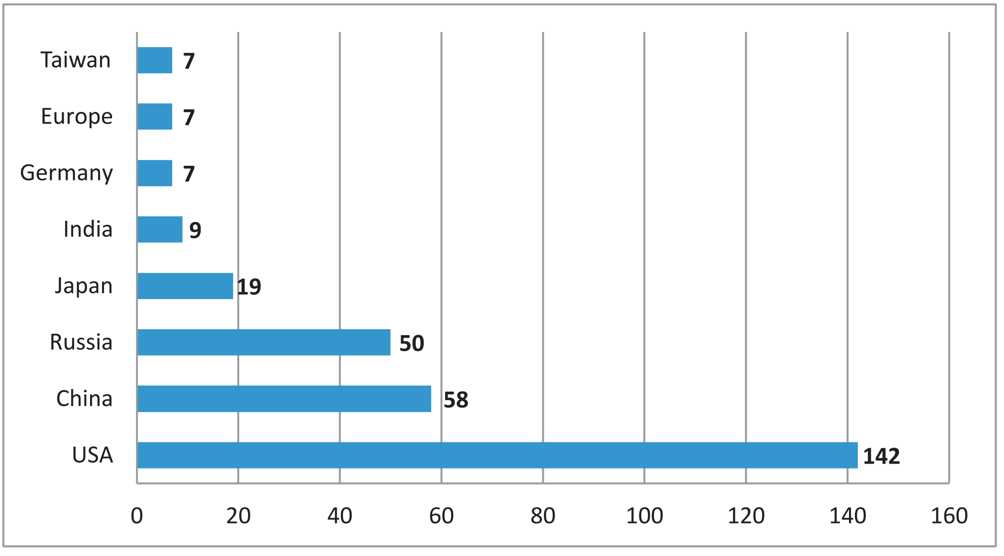
Table 9: Largest Government SmSat Operators

Type	Operator	# of satellites launched (2012-2019)
Civil	National Aeronautics and Space Administration (NASA)	51
	Russian Federal Space Agency (Roscosmos)	22
	Los Alamos National Laboratory (LANL), US	16
	Japan Aerospace Exploration Agency (JAXA)	12
	Indian Space Research Organisation (ISRO)	9
	Deutches Zentrum fur Luft – und Raumfahrt e.V (DLR)	7

	National Space Program Office (NSPO), Taiwan	7
	European Space Agency (ESA)	7
Military (based on public available information)	US DoD	58
	Russia Ministry of Defence	21
	People's Liberation Army (PLA), China	22
	Project Biarri, Australia	3
	Korean People's Army	3

Source: "Small Sats by the Numbers: 2020", Bryce Space and Technology, Bryce Space and Technology, *2020*

Figure 6: Total Number of Government Satellites (2012-2019)



Source: "Small Sats by the Numbers: 2020", Bryce Space and Technology, Bryce Space and Technology, *2020*

At the same time, SmSats also generate redundancy and their sensors are not fully capable of meeting the mission requirements of military satellites. Their weaknesses cover four specific areas. First, SmSats are constrained by orbital lifetime restrictions. The sensor technologies used for military missions generally have extended lifetimes, as opposed to conventional satellite platforms. Second, SmSats cannot accommodate instruments that consume considerable amount of power or that require high data rate transmission. Third, SmSats are small in size, which in turn reduces their capacity to accommodate large 'microwave antennas' and 'monolithic telescopes.' Consequently, SmSat platforms cannot be stabilised or maintain in-orbit stability at times. Finally, due to the small size and low power-generating capacities of the platform, a mixture of instruments are difficult to integrate.[112] Further, the footprint or coverage of SmSats in LEO is less than that for satellites in medium Earth orbit (MEO), GEO or GSO.

In an increasingly crowded LEO, having a large constellation of SmSats will be a challenge. Adjacent Satellite Interference (ASI), caused by small degrees of separation between satellites, is another challenge.[113] A congestion of satellites in LEO could lead to frequency interference from other satellites if they are closely spaced and their beams and frequency ranges overlap. However, this is a problem that satellites in high orbital belts can generate as well. Most ASI problems tend to be more acute with signal uplinks than with signal downlinks from the satellites.[114]

Other high-altitude platforms, such as UAVs and balloons, are also valuable, but these platforms also suffer from similar, if not identical, constraints as SmSats—their endurance is still limited to a few hours, which is also the case with balloons that can be sent up to at least the stratosphere. However, balloons are vulnerable to changes in weather, atmospheric winds and disruptions.[115] Indeed, mobile ad-hoc networks (MANET) in mountain and hilly terrains require UAVs.[116] Generally, satellites have enabled beyond-visual-line-of-sight ground operations, but UAVs are playing an increasingly important role for MANETs.[117] The IA is expected to acquire 5000 UAVs by 2028, which it plans to link with the Indian GPS-Aided Geo Augmented Navigation (GAGAN) system.[118] India's UAV acquisition plan is largely focused on C4ISR tasks and missions. With long-range offensive UAVs, such as the indigenous Rustom H, that are geared for anti-tank warfare under development, there is potential to conduct kinetic strikes over extended ranges, which could be facilitated by GAGAN[119] and, in the medium- to long-term, by Indian SmSat constellations.

The best approach is to link satellites with UAVs in mountain terrains for ground and air operations, and at sea with maritime surveillance aircraft. SmSats can augment beyond-line-of-sight operations of maritime UAVs, such as the Predator-B, which the IN is in the process of acquiring.[120] For air operations, a constellation of SmSats could potentially relay information via UAVs and generate continuous data transmission and surveillance for strike aircraft. The AFNet could be strengthened without having to rely exclusively on fibre optic cables for data transmission.

Generally, no single sensor system is sufficient to support C4ISR. Indeed, satellites (small and large), UAVs, balloons, and ground-based data, reconnaissance and relay stations will all be necessary for reliable and accurate information. A comparison of the orbital and suborbital information networks reveals the weaknesses and strengths of different types of sensor platforms (See Table 10). Consequently, LEO-based SmSat communications constellations are advantageous and represent a credible sensor capability that the Indian armed services can access when developed and deployed. They can meet the C4ISR requirements for military missions and can also supplement the larger satellites in GSO and GEO.

Table 10: Comparison orbital and suborbital information networks

Characteristics	GEO	LEO	HAP	UAV
Altitude	35,735 km	200-2000 km	17-25 km	0.1-20 km
Propagation Delay	120-140 milliseconds (ms)	1-15 ms	Low	Very Low
Operational Cost	Low, do not need external power supply or physical maintenance	Low, LEO satellites do not need external power supply or physical maintenance	Recovery and redeployment required	Changes with the payload type
Lifetime	10-15 years	Conditional on mission, few months or years	Few days or weeks	Depending on the power of battery, from a few minutes to single day
Deployment	Long, depending on the number of satellites in the constellation	Long, depending on the number of satellites in the constellation	Rapid deployment	Extremely fast

Source: Adapted from T.C. Tozer and D. Grace, "High Altitude Platforms for Wireless Communications", Electronics and Engineering Journal, June, 2001, pp. 127-137; Stylianos Karapantazis and Fotini-Niovi Pavlidou, "Broadband Communications Via High Altitude Platforms: A Survey", IEEE Communications Surveys & Tutorials, First Quarter, 2005, pp. 2-31; N. Hosseini, H. Jamal, J. Haque, T. Magesacher and D. W. Matolak, "UAV Command and Control, Navigation and Surveillance: A Review of Potential 5G and Satellite Systems," 2019 IEEE Aerospace Conference, Big Sky, MT, USA, 2019, pp. 1-10

SMSAT IMPLICATIONS FOR INDIAN ARMED SERVICES

Low costs and increasing miniaturisation

Trends suggest that advances in miniaturisation provides greater opportunities for the launch and use of SmSats. Growing commercialisation will foster greater miniaturisation. SmSats are a fundamentally disruptive innovation. The space industry and the national space programme are generally not used to miniaturisation, placing a higher emphasis on volume than mass, but now face the task and challenge of enabling greater miniaturisation. Thus, a new technological convergence has emerged to exploit SmSats for C4ISR.

There are several consequences to choosing to launch SmSats with an SSLV instead of fewer large satellites with bigger launch vehicles. In the coming years, SmSats and SSLVs will be cheaper. Civil-military fusion has several benefits as well. Some Chinese space startups such as Ispace, Onspace, and Galactic Energy are driving down launch costs. Similarly, launch costs will decrease as the ISRO completes the development and operationalisation of the SSLV. In addition, Indian space startups such as Bellatrix are also developing their own SSLV, known as Chetak, a two-stage vehicle capable of placing a 150-kg SmSat payload in SSO.[121] As India's space launch infrastructure grows with the establishment of new launch pads, such as the one at Tuticorin in Tamil Nadu, the armed services can leverage these capabilities for their SmSat launches. It is unviable for India to use the PSLV to launch even multiple SmSats for LEO missions. The ISRO will be unable to meet the demands of multiple privately-owned SmSat makers through the PSLV, given the launch preparation time and non-availability of the vehicle.[122]

The emergence and operationalisation of ISRO's SSLV in the coming months will make the launch costs of 500-kg payloads to LEO significantly cheaper than the PSLV.[123] Given the proximity of the upcoming Tuticorin facility to the equator, launches should become easier and cheaper as well.

SmSats and a fully functional SSLV capability are intricately linked. Clusters of SmSats for communications, remote sensing or Earth observation applications have to be launched from a single launch vehicle and deployed into their mission orbits, which could be daunting and unviable as secondary payloads on a PSLV as opposed to an SSLV. Orbital disturbances precipitated by a range of forces acting on small spacecraft such as from the moon, the Sun and the Earth are likely to be an inhibiting factor for launching a constellation in LEO. To be sure, satellites in GEO are likely to be subject to greater gravitational forces from the moon and the Sun than LEO-based spacecraft, which will be subject to the Earth's gravitational pull or atmospheric drag, inducing a reduction in orbital velocities of the LEO spacecraft. Hence, injection accuracies into mission orbits are crucial and the SSLV enables them more effectively and efficiently.

A fully operational SSLV is necessary as it can be dedicated to the exclusive launch and operationalisation of a SmSat constellation. In addition, deploying them as secondary payloads as part of rideshare launches will not be economical in all instances. Indeed, piggybacking several SmSats as secondary payloads with a primary payload might leave the SmSats with insufficient capacity due to low fuel and power to manoeuvre from their insertion orbits to their designated mission orbits.[124] Constellations or clusters of satellites using an SSLV is the best means to deploy and disperse a well networked constellation of SmSats, which will obviate strains on the limited capacities of satellite payloads to deploy in their mission orbits.

Partnering with private sector

Besides communications, SmSats dedicated to Earth observation and remote sensing have the greatest applicability. With adequate investment from the Indian armed services, remote sensing can enable greater miniaturisation and improved capacity to meet the communication requirements from small space-borne assets. As of now, the armed forces rely on the ISRO-built heavy throughput communications satellites such as the GSAT series. The Indian armed services must interact with space startups to develop SmSats communications capabilities. Combining a small set of large satellites with a sizeable constellation of SmSats is the way forward for India. This will help meet the criteria of redundancy in wartime and will mean, to some extent, greater survivability. The armed services will need to take a few risks by allocating a portion of their budget for SmSat development, even if the returns are not instantaneous. Partnering with space technology startups and private sector enterprises will help the Indian armed service meet their SmSat requirements.

Identifying SmSats that serve military applications

The rising spacecraft density in LEO make the development and deployment of large constellations risky. Potential congestion and collision are real risks for LEO-based SmSat constellations. Nevertheless, SmSats must be pursued. The integration and coordination of SmSats has in the past been fraught with difficulties given the costs of the satellites and their launch. However, SmSats have become increasingly cheaper with advances in microelectronics, power consumption and miniaturisation.[125]

Although prescribing the precise constellations that India could deploy is beyond the scope of this study, there are some points to consider. For a SmSat constellation for military applications to be effective and viable, it must be launched in clusters. The armed services can also use commercial constellations to meet their communications or remote sensing requirements, provided there is adequate security. Iridium, for instance, already operates a constellation of SmSats in LEO that the US military could potentially utilise, despite relying on large satellites in GEO since their communications systems were more stable.[126] The Iridium NEXT constellation, which is in orbit, is the only mobile satellite service that can provide voice and data coverage globally. It is also "unmatched" in terms of higher data rates, a flexible payload architecture and can be integrated with secondary payloads.[127] Other examples include SkyGlobal, a constellation of 60 satellites in LEO that is expected to provide imagery over North America, North China and Europe every 18 minutes.[128] Although these SmSat communications and imagery constellations are primarily used by non-governmental entities, governments could also avail their services.

Another approach is to wait for the launch of a commercial constellation from an Indian private sector enterprise to embed military payloads, which the US and Chinese military are already doing. Further, India could also pursue a more limited SmSat constellation instead of Iridium NEXT or SkyGlobal, but with capacities to perform a range of missions and tasks. Amongst SmSats, India could consider CubeSats, a nanosatellite whose technology was once confined to educational tasks but has now matured to exceed the performance of larger satellites in MEO while servicing communications, EO and astronomical needs.[129]

The design of a SmSat network should cover most areas of military operation. Indeed, large SmSat constellations may be more economical than small constellations of large, expensive and "complex" satellites geared for various military and national security missions located in very high orbital belts.[130]

Setting-up a Defence Innovation Unit

Exploiting the commercial space startup sector should be a core aim of the Indian armed services. Interaction between the services and the space unicorns should increase, allowing both to explore opportunities to meet the satellite-based segment of the military's C4ISR requirements. However, an enabling institutional mechanism is required, and the establishment of a Defence Innovation Unit will help facilitate interaction between the armed services and space technology startups. This has been the practice in most other space-faring nations, including the US.[131] As SmSat technology matures, it will overcome the current constraints of limited power, and transponder and instrument capacity. Indian space startups such as Bellatrix Aerospace, Dhruva and Kawa space are making space technology more affordable. The average cash-burn rate is roughly US$300,000 per month, however, the emergence of Indian space unicorns means that this rate could be spread over a year.[132] This is especially important because it reflects the declining costs of SmSats generated by space start-ups. Further, the armed services must recognise and exploit the technological opportunities from the ISRO's transfer of technology initiative to small and medium scale enterprises for development and commercialisation.

CONCLUSION

SmSats will likely play an increasingly important role for the Indian armed forces. However, they are not a panacea for the forces' C4ISR requirements. SmSats provide continuous surveillance and reconnaissance, and, if fielded in good numbers, generate a high revisit rate, boosting the military's C4ISR capability. They also help improve sensor-to-shooter capabilities and make the connectivity and data transmission between space, air-borne assets and ground stations more robust. SmSats generate redundancy and enable a more distributed satellite capability. A reasonably large constellation of SmSats will also boost the offensive capacities of the Indian armed services by relaying information in real-time across the spectrum of imaging and remote sensing through high revisit rates.

To be sure, SmSats alone might not be sufficient to meet all the military's needs. They are necessary, however, and the IA, IAF and IN must invest in them by contracting space technology startups to design and develop spacecraft to meet their requirements. It would be wise for the armed forces to consider accelerating the process of using SmSats, even as the technology evolves.

Further, SmSats are necessary because large spacecraft are vulnerable to a range of kinetic and non-kinetic threats. India has partially addressed the imbalance in offensive capabilities with the test of a KEW in March 2019. Yet despite the development of a kinetic capability and directed energy weapons such as lasers, the Indian government and the three military branches will need to expand the country's SmSat capabilities. The growing commercialisation of the Indian space technology sector creates opportunities for the IA, IAF and IN to exploit and improve its space surveillance, communications, reconnaissance and targeting capabilities. Apart from the force multiplier benefits that SmSats can bring, the goal of the armed forces should be to bring down the cost of sensor and instruments aboard SmSats to generate economy of scale, which is the objective of India's space startup industry, and to work with the private industry to miniaturise instruments carried onboard satellites.ORF

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