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Small Satellites for India's Security: A Techno-Entrepreneurial View

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Small Satellites for India's Security: A Techno-Entrepreneurial View

ABSTRACT

The past decade has witnessed the proliferation of small satellite technology in various domains including the military, academe and commerce. This paper explores the idea of utilising small satellites technology (of the order weighing less than 150kg) for specific aspects of India's space security interests. It will describe some of the programmes and missions of global leaders in space security, and examine specific applications of small satellite technology in areas such as Imaging, Automatic Identification of Ships, Wireless Distributed Sensor Networks and Electro-magnetic emission mapping. From a policy viewpoint, the need for a defence innovation policy within India is presented in this study, as well as comparative analyses with similar policies in the US Army. The paper offers recommendations for promoting defence innovation in the country that could create an ecosystem conducive to Indian entrepreneurship, not only to cater to the country's needs, but potentially to export to the world.

INTRODUCTION

The terrain of space exploration in Low Earth Orbit (LEO) has been continuously evolving and one can argue that small satellites have tremendously changed this terrain over the last three decades. The ongoing debates—small vs. large satellites, the size that constitutes 'small'—are not related to capability or capacity, but rather their ability to complement each other's platforms and overcome disadvantages.

This paper examines the continuously evolving technology and applications of small satellites of the class of <150kg. These small satellites are often missions with a two- to five-year timeframe. This study probes the potential of extending small satellite technology to space security through a study of adaptation and experimentation by stakeholders in the industry.

Small satellites provide strategic users with affordable satellite constellations that have excellent tactical and theatre control capabilities designed for specific operations. Some of the key advantages of using small satellites include the following:

- Unlike large satellites, small satellites can operationalise usage with minimal personnel and logistics tail. This advantage is due to their specific design for tactical warfare: in mission scenarios, they act as 'gap fillers' for their larger counterparts.
- Larger satellites often have mission durations of over five years, inherently shortening their shelf life due to rapid technological changes on space-based platforms. Small satellites provide an excellent opportunity to take advantage of the constantly upgrading technologies to provide complementary technology capabilities.
- Small satellites offer a unique opportunity to integrate satellites at low cost per unit due to a combination of factors, such as using Commercial Off The Shelf (COTS) components along with simpler design philosophies due to their operational lives being internationally kept lower (to cope with constant cost/technology upgrades.)
- Small satellites provide augmentation and reconstitution at extremely rapid timelines. These are inherent advantages due to their rapidly design-build, short-notice deployment responsiveness. Low-flying constellations also provide graceful degradation.
- They provide an opportunity to task from theatre and in a constellation, their configuration can provide persistent and globally available capabilities. Small satellites, especially in constellations, have extremely low volumes per unit, considering

their larger counterparts. Thus they offer excellent survivability against Anti-Satellite (ASAT) engagement. The cost ratio in engagement of such constellations may often not favour the engager (provided the ability to be operationally responsive).

APPLICATIONS OF SMALL SATELLITES

The possibilities of hosting services for Command, Control, Communications, Computers, Intelligence, Information, Surveillance, and Reconnaissance (C4I2SR) based on small satellites have substantially increased with the miniaturisation of payloads. There are now a host of applications enabled by small satellites (particularly in swarms) that can transform the usage of the final frontier for intelligence gathering and tactical use.

The small bouquet of applications mentioned in this section includes examples of current mission scenarios that are being used by several leading spacefaring countries to effectively use small satellite technologies in C4I2SR. It is important for India to have a roadmap in effectively testing some of these technologies within the country and in deploying them in operational usage at the grassroots level for effective ground utilisation of advanced technologies.

Electro-magnetic emissions

One of the unique Electronic Intelligence (ELINT) operational programmes that are possible on small satellites is to map and characterise electromagnetic emissions (such as radars) around the world. Electromagnetic emissions such as ground radars are typically used by defence establishments for tracking airspace activity. Space-based mapping of the ground radars should provide an opportunity to develop airspace tracking hotspot databases used for electronic warfare that can be key to detecting and monitoring activities during tactical operations.

One of the mission examples of such a space-based system of small satellites for electromagnetic emission intelligence is the one launched by the French Defence Procurements Agency (DGA), called the ELISA (ELectronic Intelligence by SAtellite) and ESSAIM swarms with ELINT payloads carried on-board four Myriade class micro-satellites.[1]

Launched in 2004, ESSAIM also has four Myriade platform-based micro satellites flying in formation through space, analysing the electromagnetic environment on the ground in a number of frequency bands used exclusively for military communications.[2] Similarly, ELISA was launched in 2011 for space-based electronic intelligence mission for mapping global radar activity index.[3]

As a follow-up mission to ELISA and ESSAIM, France is building the CERES (Capacité de Renseignement Electromagnétique Spatiale or Space Signal Intelligence Capacity) system comprising three closely positioned satellites designed to detect and locate ground signals with operational service from 2020.[4] CERES shall remove the overflight constraints and provide all-weather military electronic intelligence to gather signal intelligence from areas that surface sensors cannot reach.[5] The program has been contracted to Airbus Defence & Space and Thales Alenia Space.

The transition from ELISA, to ESSAIM and to CERES is an excellent example of buildup to using small satellites in swarms for gaining an in-depth situational picture to support the conception and execution of military operations via on-orbit resources.

Imaging

Imaging satellites have taken a giant leap with the miniaturisation of technology and emergence of reliable low-cost electronics for space systems. There is huge potential for using small satellites to complement the traditional legacy imaging platforms of the Indian Space Research Organsiation (ISRO) such as the CARTOSAT series of satellites. This should fill the gaps in latency and cover particular areas of interest with a frequent revisit.

Small satellites used for imaging can be used in tactical warfare along with Unmanned Aerial Vehicles (UAV). DARPA's SeeMe programme is one example of how small satellites can offer operational support for tactical warfare. Under this programme, a network of 24 satellites delivers 24/7 individual warfighter imagery using a small satellite. With a 90-day call-up period, these satellites are built at less than $500,000 each and provide sub-meter resolutions.[6]

The miniaturisation trend has brought about a giant leap for commercial imaging satellites. After 2010, Sky Box Imaging showcased a satellite providing 0.9m Panchromatic (PAN) and 2m multi-spectral (at 450km). The platform also provides video of 30 frames per second, duration up to 90 seconds, field of view 2 km by 1.1 km, resolution 1.1 m.[7] Following such capabilities built into small satellites, constellations are now gaining in commercial viability, with Planet Labs launching over 100 satellites,[8] and BlackSky Global building 60 satellites providing 1m resolution on 50kg platform.[9]

In a most recent trend, UK's Surrey Satellite Technology Ltd (SSTL) reports to have built the 80-kg Carbonite-1 in a short period of six months with an online purchased camera and telescope (25cm mirror) adapted for space environment, providing a ground resolution of 1m (from 500km). SSTL wants to further reduce the platform to 50kg at a cost of less than a million pounds per satellite.[10]

Miniaturisation has not only taken effect in PAN and multi-spectral imaging, but has also provided possibilities for Synthetic Aperture Radar. In one such development, Japan is working on developing a 100-kg X-Band SAR satellite with a budget of less than $20 million and providing a resolution of 3m/10m.[11]

For India's ISRO, its current roadmap shows the development of MICROSAT-1, a platform that matches some of the missions earlier described.[12] However, there is tremendous scope for the expansion of the small satellite programme to enable these platforms to be used as gap-fillers with larger cartographic satellites that can enable strategic users to gain near-real-time insights.

Automatic Identification of Ships (AIS)

India has a long coastline of some 7,517 km and yet the current capabilities in monitoring vessels along the Indian coastline is limited to using radars, which have inherent horizon limitations, and AIS receivers on lighthouses under the National Automatic Identification System (NAIS).[13] There are 74 lighthouses fitted with the Swedish SAAB systems for the Directorate General of Lighthouses and Lightships (DGLL), which will also be used by the Indian Navy, Coast Guard and Directorate General of Shipping.[14]

This project, however, limits the capability of Indian users to the horizon visibility of the receivers installed. There is a need for a comprehensive AIS system that will not only provide insights of the ships around the Indian Ocean but also provide key analytics of the shipping patterns across the globe. Such capability, combined with identification of dark ships using Synthetic Aperture Radar (SAR) imaging, can provide key intelligence for maritime security. With several generations of AIS receivers now flown on-orbit, small satellites offer an excellent platform for deploying a swarm of these receivers on-orbit for low-latency operations.

Internationally, one of the earliest concepts of maritime monitoring of vessels using small satellites was presented by the Norwegian Defence Research Establishment.[15] Several commercial industry players—such as Space Quest, ORBCOMM and exact Earth (a subsidiary of COMDEV)—now also play a larger role in maritime monitoring with AIS receivers in space. More recently, a NewSpace company called Spire, received a large investment to create a constellation for small satellites-based AIS.[16]

Space-based AIS is only relevant for cooperative targets (ones that broadcast their position, velocity, heading, among other critical parameters). Non-cooperative targets, however are dark ships/vessels who do not broadcast. Therefore, in order to have an effective space-based monitoring system, a sensor data fusion between AIS along with satellite-based SAR provides valuable information to complete the maritime picture. Such sensor fusion shall provide detection of vessels with and without AIS over large areas with day/night, all-weather capability. This can also be used for other applications such as detecting oil spillages.

With its long coastline, India should find such combination of technologies highly cost effective when compared with traditional patrol vessels deployment. However, it is important to understand that space-based technology alone cannot solve all maritime surveillance problems in the detection of vessels. For example, the collection of imagery SAR is mainly on a snapshot mode and comes with some time delay between acquisitions and information delivery (although AIS is real time). A user must have an Area of Interest (AoI) prior to data collection.

Maritime detection of vessels is thus more of an amalgamation of technologies and systems that are ground-based, space-based and vessel-based. With a range of technologies available—from AIS, to Vessel Traffic Services (VTS), coastal radar (active and passive), Long Range Identification and Tracking Systems (LRIT), Satellite-based AIS, Satellite-based Earth Observation, Airborne Remote Sensing, and emitter localisation—each of these systems have their own benefits and disadvantages.[17] Users need to harness the benefits while complementing their weaknesses with parallel technologies.

As for space-based maritime surveillance, a combination of AIS with SAR on a single platform in a constellation[18] around the Indian Ocean seems an excellent avenue to explore maritime security for the Indian subcontinent. Further, developing space-based AIS receiver technology can provide baseline capabilities into other important communications applications including Automatic Dependent Surveillance–Broadcast (ADS-B), tracking applications for cargo and equipment which may be of interest in both civilian and defence domains.

Wireless Distributed Sensor Networks

Wireless Sensor Network (WSN) may essentially be made of spatially distributed autonomous sensors to monitor the local physical and environmental conditions and cooperatively pass their data through a network.[19] Combined with a communication link to small satellites, WSN can be applied to C4I2SR and allow for low-cost, low-power, multifunctional, tiny sensor nodes that can be installed to cover large areas of interest to sense the environment for real-time monitoring.

Extensive studies have been conducted on using both passive and active sensors to detect and measure various characteristics of a target including its magnetic, thermal, or acoustic signature, as well as to measure a target's presence, range, velocity, or direction of travel by how the target modifies, reflects, or scatters a signal transmitted by the sensor.[20] A case study on vehicle detection and tracking using wireless sensor networks has already showcased the potential of deploying sensors on the fly that can operate unattended, without the need for any pre-existing infrastructure and requiring little maintenance.[21]

In one such example, the US Army is working with Terran Orbital Systems for distributed sensor monitoring and asset tracking using small satellites.[22] Terran Orbital intends to launch small satellites at lower altitudes (typically 600km) which makes it convenient for low-powered, disposable, sensors to use a satellite data link to track vehicles and troops that transmit at tens of kilobytes per second.[23]

Provided the large surveillance and tracking needs of the long Indian borders, small satellites combined with distributed WSNs potentially offer tremendous opportunities for deployment of thousands of sensors that can effectively compliment the current methods of C4I2SR.

ARCHITECTING SMALL SATELLITES FOR C4I2SR

A primary reason for the upsurge in the use of small satellites has been the effective miniaturisation of spacecraft technologies, resulting in savings in mass, volume, power with better cost, and throughput. In the context of small satellites-based space security, the primary focus in this section is to highlight specific sensor and subsystem technologies that technologically elevate small satellites-based missions and applications to provide operational service capability that is technologically matched with larger satellites.

Some of these technologies may be specifically designed with a primary intent of operationalising the technology on a small satellite. The design can also include specific COTS approach to enable commercialisation on flight heritage. The following technologies have been identified as key-enablers on small satellite platforms that should make a strong case for using them independently and in swarms for specific C4I2SR applications.

Plug-and-Play designs tactical users

Small satellites provide scope for the architecture of customised applications for tactical users. Depending on the need of the user the bus architectures may be designed to be modular, in a completely Plug and Play manner to provide responsive capabilities at a rapid timescale. These may also be built using an open systems framework by often combining commercial standards with carefully chosen COTS hardware and software as necessary to deliver real-time capability at a lower cost factor.

Using such architectures in design might very well lower the on-orbit lifetime of the satellite. However, this provides capabilities to seamlessly integrate payload and spacecraft bus for rapid deployment from alert status for launch to theatre control within a short span of time (often less than one week from a stored state). The United States Department of Defence (US DoD) via its Air Force Research Laboratory (AFRL) is a prime example of invoking methods and processes such as machine negotiated interfaces, Appliqué Sensor Interface Module (ASIM), Push-button Toolflow, and Test bypass to enable such architectures.[24]

Inspired by 'Space Plug-and-Play Avionics' (SPA), AFRL has evolved the concept of 'six-day spacecraft' over a decade through its ORS, Plug-and-Play satellites (PnPSats), and Tactical Satellite (TACSAT) series missions. While there are reports that not one of these satellites have been built in six-days until now, the learnings on developing modular architectures for rapid development and integration is considered valuable for their insights into developing completely Plug-and-Play designs for future missions.[25]

Optical Laser Transmitters and Ground Segments

One of the main bottlenecks in retrieving data from an Earth Observation (EO) satellite is the window available to downlink data. This is traditionally solved by using several ground stations across the globe. However, most satellites still need to use image compression techniques to reduce the size of the data in order to transmit to the ground the specific scene sequences they capture. The compression is done to ensure that the generally available transmission window of about 10-15 minutes (depending on the orbit height and the pass with respect to the ground station) is used effectively to downlink larger volumes of the scenes.

This trade-off of using compression and downlinking the data will then lead to the need for de-compression of the data before further processing. Therefore, the traditional RF links-based transmissions and reception pose some challenges to the quality of the information. One of the emerging technologies that can leapfrog the quality of EO data and facilitate high-speed communications links is the emergence of the optical laser transmitters. These transmitters have several important features against the traditional RF transmissions when used in satellites, including the following:

- Data rates of 1 Gb/s already available with current research for 10 Gb/s transmitter underway.[26]
- They can facilitate point-to-point communication involving multiple platforms such as UAV, aircraft, High Altitude Platforms (HAP) and satellites.
- Inter-platform, platform-to-ground, platform-to-satellite links for a wide range of operational scenario applications.
- They generally have reduced mass, power and volume against their Radio Frequency (RF) counterparts.
- Unlike the RF links there is no license costs, no usage restrictions, and no International Telecommunications Union (ITU) spectrum regulation. This is also of strategic interest since there is no need of declaring the spectrum and the bandwidth internationally.
- Laser links can be highly robust against interception, jamming, or spoofing due to narrow beam divergence, and make a case for stealth communications.
- The unique feature of using laser communications is the ability to use narrow optical beam diameters (limited signal spread) directly to secure optical downlinks. The link facilitates a user-specific identifier on the uplink beacon. Thus there is a case for interception and encryption-proof communications.

Several spacefaring countries including Germany, Japan, the US and France, are supporting the development of optical laser communications. Germany's DLR Institute of Communications and Navigation has an Optical Space Infrared Downlink System (OSIRIS) project that is using COTS hardware to obtain a cost-effective approach to develop optical communication technology optimised for small satellites. The Laser Communication Terminal (LCT) developed by German Space Agency (DLR) has already proven an inter-satellite 'duplex' laser link of 5.6 Gbps with its Terra SAR-X and NFIRE in-orbit tests in January and February 2008.[27]

A key feature of the DLR's advances is the development of the transportable Optical Ground Station (OGS) to allow for optical downlinks at arbitrary locations on Earth. The OGS is built as a foldable mount structure that fits into a standard air-freight container and can be set up in only a few minutes. The OGS has a GPS-aided levelling and alignment that allows for day- and night-time deployment, without any reliance on star calibration.[28]

Tests done by DLR have indicated that with a 60-cm Transportable-OGS,a data rate of 1 Gbit/s can be reached at an elevation angle of 20°. While the S-band RF link with best conditions of minimum link elevation of 5° and an availability of 100 percent enables the transmission of roughly 4 Gbit per day, an OGS with comparably high minimum link elevation of 20° and poor availability due to cloud cover still enables 200 Gb/day. According to DLR's theoretical calculations, using its Optical Ground Station Oberpfaffenhofen and the transportable-OGS, the mean daily throughput can be increased to reach 1 Tb/day (250 times S-Band RF link).[29]

Similar international developments include the following:

- NASA-JPL is currently performing a technology demonstration aboard the International Space Station (ISS) for its Optical Payload for Lasercomm Science (OPALS) experiment for interconnectivity between near-Earth assets.[30] JPL is currently studying a compact optical terminal with a 5-cm aperture diameter for LEO applications. The flight transceiver capable of a 10Gbps downlink data rate with a

0.6-m ground telescope is assumed as a receiver.[31] Laser Communications Relay Demonstration Project (LCRD) is envisioned to test high rate bi-directional communications between Earth and Geostationary Earth Orbit (GEO) with a real-time optical relay through Earth-GEO-Earth using Differential Phase Shift Keying (DPSK) and Pulse Position Modulation (PPM) modems. With current tests already showcasing the possibility of data rates exceeding 2Gbps, data replays of rates beyond 10 Gbps is envisioned for future relay scenarios.[32] LCRD is expected to be flown as a commercial satellite payload in 2017.[33]

- The Swiss company RUAG Space, with the support of the European Space Agency (ESA), is developing the OPTEL direct-to-ground laser downlinks from LEO satellite providing up to 2 Gbit/s data rate.[34]
- Japan's National Institute of Information and Communications Technology (NICT) initiated Small Optical Transponder (SOTA) for micro satellites to demonstrate the optical technology (of 10 Mbps) via its Space Optical Communication Research Advanced Technology Satellite (SOCRATES) project.[35] With the success of the acquisition tracking and pointing functions of SOTA in the data transmission test through atmospheric turbulence, there is a planned integrated test with the small satellite bus.[36]
- Based on the French Space Agency (CNES) Liaison Optique Laser Aéroportée (LOLA) programme of testing high data rate optical communications between satellites and airborne or ground users, a LEO downlink terminal demonstrator is planned in 2018 to test connections of 20Gbps.[37]

Although cloud cover may hamper communications while using optical laser terminals, there is a significant benefit in utilising a ground network that will allow downlinking on a regular basis (on a similar basis of RF). Building core capabilities in utilising both RF and optical-based communications as complimentary technologies can provide an 'eye in the sky' capability with immediate data relay to users located within the areas of interest. This can significantly change the outlook of operational use of laser terminals for EO data and in the near future communications links from GEO.

On-board processing

One of the key elements of responsive space is the ability of space assets to provide concrete intelligence in near-real time. While traditional EO satellites may use a chain of data collection, on-board compression, transmission to ground station, data processing and eventual return to the user with best return times of acquisition to data processing to a few hours, rapid response space assets can be built to support C4I2SR missions to facilitate this chain of activities within a few minutes. This can mainly be done via the architecture of an on-board processing capability within the satellite to process the data acquired for a specific scene.

An example of customising on-board processing on responsive satellites to tactical usage can be found in the Tactical Satellite (TACSAT-3) mission led by the United States Air Force Research Laboratory. The satellite uses an Advanced Responsive Tactically-Effective Military Imaging Spectrometer (ARTEMIS) designed by Raytheon Space and Airborne Systems with collaboration on the imaging spectrometer from the Jet Propulsion Laboratory as one of the first responsive space payload developments that use COTS based hyperspectral imaging for spectral matching, indication, and identification of elements using automated routines.[38]

The satellite has been designed so that once the hyperspectral cube and the panchromatic image is taken, the on-board processor will analyse the region of interest for objects of interest and will then geo-rectify the location of these objects with the panchromatic image upon which the tactical user will be provided with a panchromatic image of the region with icons on the image that represent locations of the objects of interest.[39]

This architecture is mainly driven by integrating a sensor processor that autonomously processes the data allowing a tactical user to request a hyperspectral analysis of a given region for specific objects and gaining responsive intelligence often in less than 10 minutes.[40]

Customising user segment, integrating analytics and APIs

A crucial challenge in the operational usage of satellites on the ground is the ability to provide technological backbone to handle the volume, variety and velocity of data. While this relates to the dimension of satellite technology, an important aspect of support for tactical operations is the ability to customise user segment for strategic users.

The challenge therefore in customising the user segment may include facets such as the ability to provide faster insertion of high-bandwidth communications, improved link reliability, reduced transportation costs, rapid contingency or back-up solutions, and employing customised processing chains for the quick assessment of spectral signatures of threats.

Customising user segment, for example, can be done in portable ground systems. With support and funding from the US DoD, GATR Technologies is currently one of the only inflatable ground systems developer in the world.[41] GATR has combined ultra-lightweight materials, an inflatable design, and proprietary manufacturing techniques to develop a series of deployable communication systems that provide a large-aperture satellite communication system packaged in carry cases in an effort of reducing logistics costs, while improving voice, data, and video communications for forward deployed forces.[42]

Another example in the imagery side is of customising data processors for tactical users. Harris Corporation, for instance, offers integrated processing and analytics solutions which enable near real-time action and decision-making. Once the imagery is collected, it is matched with spectra of the target signatures, automatically chips out relevant geo-located target images, and automatically identifies and classifies target materials, creating intelligence products to enable near real-time decisions and action.[43]

The next generation of customising user segment shall move towards integrating Application-Specific Integrated Circuits(ASIC) into user segments to micro-miniaturise functionality and provide real-time insights in tactical warfare.

Green Propulsion for LEO

The propulsion system is a key technology that should enable orbit correction which are especially relevant to low-flying satellites. Traditionally, hydrazine has been used as hypergolic bipropellant with nitrogen tetroxide or in a monopropellant thruster with a catalyst on space systems due to its hypergolic multipurpose nature.[44] Hydrazine and nitrogen tetroxide are also mostly used in missions that require long-term storage due to their 'storable' characteristic of remaining stable at room temperature for a long periods of time (months or even years).[45]

For example, the Indian Mini Satellite (IMS-1) bus carries a propulsion system using a single 1 N thruster, mounted centrally and mainly used for orbit correction that is fuelled using a single tank carrying 3.5 kg hydrazine.[46] However, propellants such as hydrazine is risky due to its highly corrosive and toxic nature. Several space agencies therefore are working on developing 'green' propulsion systems that should enable easy handling of propellants while deriving the same technical performance.

Green propellants can eliminate the usage of specialised facilities, personnel, and ground-support equipment of a traditional fuelling effort. Green propulsion thus has tremendous potential in ensuring the health and safety of technicians and engineers while helping save cost in ground handling and in timelines of building satellites.

Green propulsion is an enabler for rapid satellite deployment capabilities. An example of a space security-focussed mission using such architectures is the T2E (Tier-2 Enabler) Technology Demonstration Mission of the Operationally Responsive Space (ORS) Office of the US Department of Defense.[47] Green propulsion is also now being explored with small spacecraft such as CubeSats. NASA for example is funding the development of green propulsion technology called the CubeSat High Impulse Propulsion System (CHIPS).[48]

Green propulsion has also gained traction in the international industry with examples of successful development of High Performance Green Propulsion (HPGP) and on-orbit demonstration by Ecological Advanced Propulsion Systems (ECAPS), a subsidiary of the Swedish Space

Corporation (SSC).[49] The HPGP propulsion system, which has undergone 10 years in R&D, has been successfully demonstrated on-board the PRISMA spacecraft since 2010 and has reported about a 32% higher ΔV capability over hydrazine.[50]

With the SkyBox Imaging contract award of 12 complete HPGP propulsion system modules for the SkySat constellation (high-resolution imaging and video-capable satellites) there are definite signs of commercial EO companies already employing green propulsion technologies as well.[51] In fact, SkyBox Imaging has already reported that the HPGP solution selected provides nearly twice the on-orbit ΔV considering the more traditional monopropellant systems.[52]

Green propulsion may hold the key for rapidly deploying low-flying spacecraft swarms with a completely on-orbit, on-demand re-configurability to provide significantly improved mission flexibility, enabling collection and delivery of higher quality and more timely data to C4I2SR users.

3D printing

The use of additive manufacturing via 3D printing has gained immense traction in the past decade in several technology sectors with its ability to enable rapid prototyping with distinct features of saving of costs (in labour and material), and time in the process of manufacturing.

Several initiatives have recently begun to look at implementing 3D printing for space activities in both satellites and launch vehicles. While NewSpace companies such as Rocket Lab are looking to print engine parts for their rockets,[53] several core-3D printing technology companies alongside traditional aerospace companies such as Boeing[54] and Lockheed Martin[55] have set their eyes on leveraging rapid prototyping and inherent cost benefits of 3D into spacecraft buses.

The technology of 3D printing is making its way to additive manufacturing of external spacecraft parts. NASA JPL, in partnership with Stratasys Direct Manufacturing, has made advances in 3D printing of external satellite parts by manufacturing antenna parts for FORMOSAT-7

Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC-2) using Fused Deposition Modelling (FDM) with ULTEM 9085. The material has properties of being qualified for spaceflight that includes a high-strength, engineering-grade thermoplastic with excellent radio frequency and structural properties alongside its high temperature and chemical resistance. With the core aspects of the technology reaching NASA Technology Readiness Level 6 (TRL-6), these will be flown in 2016 in six satellites.[56]

Further, there is room for fabricating critical subsystem parts such as propulsion tanks with increased reliability. One of the recent developments is the success of Aerojet Rocketdyne in showcasing its MPS-120 CubeSat High-Impulse Adaptable Modular Propulsion System (CHAMPS) for CubeSats. Funded by the NASA Office of Chief Technologist's Game Changing Opportunities in Technology Development, it is claimed to be the first 3D-printed hydrazine integrated propulsion system designed to provide on-orbit thrust for CubeSats.[57]

3D printing can enable the integration of advanced technologies in small satellite platforms by facilitating the integration of sensors and components in a minimised volume in a short turn-around time. This in turn should reduce the mass of the entire bus and also provide an ability to customise design for adding protection to critical components. An advantage of 3D printing technology, specifically for small satellites, may be the gain of minimising labour hours in the loop of integrating satellites. This not only saves labour costs but also facilitates the seamless integration of electronics into the spacecraft bus interface.

3D printing provides immense opportunity for embedded wiring that should in turn enable efficient embedding of electronics and communication systems. It also allows for the wireless plug and play within spacecraft buses. Core issues of space environment—such as radiation shielding, thermal cycling/management, and electromagnetic properties—can be addressed using specific material alternatives within the spacecraft bus.[58]

These technologies are just a few of the trends in some of the core verticals of satellite technology. In fact, NASA's Small Spacecraft

Technology Program (SSTP) has conducted an assessment of the current state-of-the-art small spacecraft technologies for satellites below 180kg, which clearly maps the rising trend of subsystem capabilities that are being built for the operational use of these satellites.[59]

Given current capabilities in the country, without the participation of academia and industry, it is virtually impossible for state-run organisations alone to develop all these technologies within a timeframe that will elevate the country's current technology landscape to state-of-the-art. It is therefore important to create umbrella programmes that will create an environment for the active participation of industry and the academe in the development of state-of-the-art technologies.

SMALL SATELLITES FOR C4I2SR & TACTICAL USAGE: A CASE STUDY OF US AGENCIES

Several US defence agencies have forayed into the potential of small satellites for C4I2SR tactical usage. Besides the traditional civilian space (NASA centres), academic and industry partners, there has been interest amongst several government agencies to participate in using small satellite technologies in tailoring platforms to suit their particular applications.

Government agencies participating in the development or use of small satellites include the Naval Postgraduate School, Naval Research Laboratory, Army Space and Missile Defense Command (SMDC), Air Force Space and Missile Center's Space Test Program (SMC/STP), Operationally Responsive Space (ORS) Office, Defense Advanced Research Projects Agency (DARPA), Space and Naval Warfare Systems Command (SPAWAR), Air Force Research Laboratory (AFRL), National Reconnaissance Office (NRO) Survivability Assurance Office (SAO), U.S. Special Operations Command (USSOCOM), Department of Homeland Security (DHS), Defense Intelligence Agency (DIA), Central Intelligence Agency (CIA), and the National Security Agency (NSA).[60] The most prominent missions include the following.

DARPA

The Defense Advanced Research Projects Agency (DARPA) is running a programme called Space Enabled Effects for Military Engagements (SeeMe) which is proposing to use small satellites swarms for warfare support for multiple units deployed simultaneously with handheld devices that support their operations. The programme suggests that there are no logistics or maintenance costs beyond the handheld devices, therefore having a direct link between low orbiting swarms.[61]

As part of the responsive launch for putting up small satellite in very short-notice periods, DARPA is running the Airborne Launch Assist Space Access (ALASA) programme to leverage the flexibility and re-usability of an air-launched system with a goal of inserting 100-pound satellites into low Earth orbit within 24 hours for less than $1 million per launch. With the successful initial phases of realising sufficient maturity of technology, DARPA's first ALASA flight demonstration test was scheduled for late 2015 and the first orbital launch test, in the first half of 2016.[62] Although this program was eventually scrapped, ALASA further symbolises the importance of responsive launch capabilities in the realm of space security.

Other than the SeeMe and ALASA programmes, DARPA has also solicited proposals for inter-satellite communications links using small satellites. The small satellites are expected to delivery high communication data rates (>1 Mbps) having a per-link average weight of less than 2 pounds with a power dissipation of less than 3 watts (on-orbit) requiring development within 24 months.[63]

US Army

The US Army Space and Missile Defense Command/Army Forces Strategic Command are engaged in programmes such as the Space and Missile Defense Command (SMDC) which strategically use small satellites for expeditionary capabilities, with the intention of reaching an unprecedented low level of mission command. The responsive space initiatives are primarily focussed around tactical war needs and the small satellite capabilities are designed to be directly employed by small unit forces.[64]

With a cost of less than $350K/spacecraft, eight nanosatellite technology demonstrators were delivered within 12 months to demonstrate over-the-horizon communications technology for tactical forces with an operational life of greater than 12 months in LEO. The spacecraft demonstrations are said be extremely successful for over-the-horizon communications and extraction of military terrestrial hardware data.[65]

Nanosatellite Program (SNaP) is another such technology demonstration mission that is currently being pursued for beyond-line-of-sight communications and data exfiltration. SNaP is a 5kg satellite at a cost of about $500,000 designed for resilient communications when traditional satellite communication is unavailable due to line-of-sight issues or due to a denied or degraded environment. Three SNaP satellites flew in October 2015 to test the low flying satellite communications technology that shall take advantage of the much lower signal levels to be received and processed.[66]

The US Army is also running a low-cost imaging demonstration mission called Kestral Eye to showcase near-real time imagery relay directly via data relay network accessible to the ground forces with the satellite taking a picture of a designated ground object of interest relaying back within an approximately 10-minutes (tasking-to-product cycle). The satellite built by Maryland Aerospace is said to produce 1.5m resolution imagery (from 450 km) on an 18kg spacecraft with a cost of < $1mil per spacecraft in production mode for an operational life of more than a year.[67]

While Kestral Eye Block 1 is expected to be launched in 2016, SMDC has already contracted Andrews Space[68] to build the Kestral Eye Block 2 as a 30kg spacecraft producing 1.5m GSD imagery at a cost of $1.3mil/unit with similar tasked from theatre capabilities.[69] Successful on-orbit demonstration of this may revolutionise the operational use of small satellites as an addition to tactical capabilities based on imagery.

Other prominent missions of the government agencies include the following:

- NRO's Advanced Systems and Technology Directorate runs Colony I and II programme with small satellite architectures with a set of minimum specifications useful for government applications.[70] Although the references to the Colony point towards Space Weather,[71] it is unclear as to what payloads are exactly being flown.
- The US Navy is launching an Integrated Communication Extension Capability (ICE - Cap) project to address polar communications shortfalls by a satellite cross-link from a LEO small satellite to a Mobile User Objective System (MUOS) satellite in GEO to instantaneously relay information to a terrestrial data network.[72]
- The Development Planning Directorate at the Air Force Space and Missile Systems Center (SMC/XR) is running the Space Environmental Nano Satellite Experiment (SENSE) to test the performance of small satellites for operational space weather missions by putting two satellites into orbit to carry three Space Environmental Monitoring (SEM) payloads designed to characterise Total Electron Content (TEC), ionospheric scintillation, ion and neutral winds composition, and ionospheric UV nightglow.[73]

Missions by several defence agencies are only expected to go up in numbers as the adoption of small satellite technologies alongside dedicated launch opportunities become prevalent over the next few years.

Given the technology miniaturisation landscape and the possible applications in swarms, there is a need for India's defence establishments to seriously consider a program for the operational use of small satellites to complement the use of current legacy satellite systems.

INSIGHTS ON RESPONSIVENESS OF SPACE ASSETS FOR C4I2SR

Intelligence gathering is the first step in the process of making coordinated strategies for choosing whether or not to act on such information. In the realm of C4I2SR, the value of intelligence gathered in real-time against that of having a multi-stakeholder chain of gathering, processing, and hand-over of intelligence for eventual actions, may immensely affect the outcomes of several case scenarios.

Therefore, with the rapid evolution of technology there is also a case for continuously evaluating the chain of intelligence gathering alongside the decision-making chains against such leapfrogging technology regimes. Overhauling space assets alone cannot deliver value to tactical users. Real value for tactical users lies in overhauling the processes and technologies from the point of decision to building a specific use case to delivering it for the ground user to be able to tap into the asset in the least possible timespan. In order to build such capabilities in space-based C4ISR one has to take note of building responsiveness—not just of the space assets once in orbit but in responsiveness in getting the space asset up as well as in enabling the ground user to directly use the asset with real time capability. Therefore, responsive ground decision-making chains and responsive launch capabilities shall remain key to overall ability of armed forces to be able to be able to leverage space as a real-time theatre control frontier.

Responsive decision-making chains in command of space assets

Decision-making chains in C4I2SR can be extremely challenging since the blocks of organisations of a particular decision-making chain can be long and there can often be a hand-off to different stakeholders within the system. These hand-offs or hand-holding may be a necessity due to the technological infrastructure and know-how being available with particular blocks within the system. These decision-making chains therefore have a direct impact on the latency of the action, starting from the request for acquisition of intelligence to the time of return of the intelligence.

Considering the importance of low latency in decision chains of C4I2SR, there is a need to introduce such decision-making chains into using of the space-based assets of the country for effective ground utilisation. It provides an overview of different decision chains for using space-based assets in C4I2SR and eventual utilisation of intelligence. There are three case scenarios for decision-making depicted with decreasing latency in decision-making.

Case A

The classic case of usage of space assets for C4I2SR (especially geo-intelligence via imagery) is leveraging the space-based technology infrastructure available for gathering intelligence for specific areas of interest (cartographic/resource monitoring satellites in case of imagery specific intelligence).

In such a case of armed forces using civilian space assets (dual use of technology), there is a mechanism of coordination that is needed between the times of request for intelligence to the hand-off of such a request from the domain of forces to the civilian realm. Such an operational mechanism will then involve the civilian chain handling the intelligence request and tasking space assets in acquisition of relevant intelligence, receiving at their stations with eventual processing and hand-off of the intelligence along the same lines of communications between the civilian and the armed forces chain of command.

The latency of such an operational regime not only poses immense challenges in bureaucratic stages involved in such hand-offs, but also has a potentially eroding effect (sometimes exponential) on the quality of the intelligence. This then becomes a step towards the armed forces pushing for an independent command and control chain as an effort of potentially decreasing the latency in decision-making in removing the civilian operations segment.

Case B

The need for decreasing latency as posed in the former case may take form by creating civilian equivalents of intelligence gathering, processing establishments within the C4I2SR realm. In missions such as CARTOSAT-2A/2B, the satellites have been commissioned to be built by the Ministry of Defence for dedicated scene-specific spot imagery in high resolution for armed forces,[74] the development of the technology infrastructure (space and ground) and the training can be provided by a dedicated space establishment (in this case ISRO). This is a step ahead of avoiding several stages of bureaucratic hand-offs in information between the civilian and defence realm, however, the chain of utilisation still has the presence of a nodal agency within the C4I2SR ring which may act as a front for facilitating the intelligence.

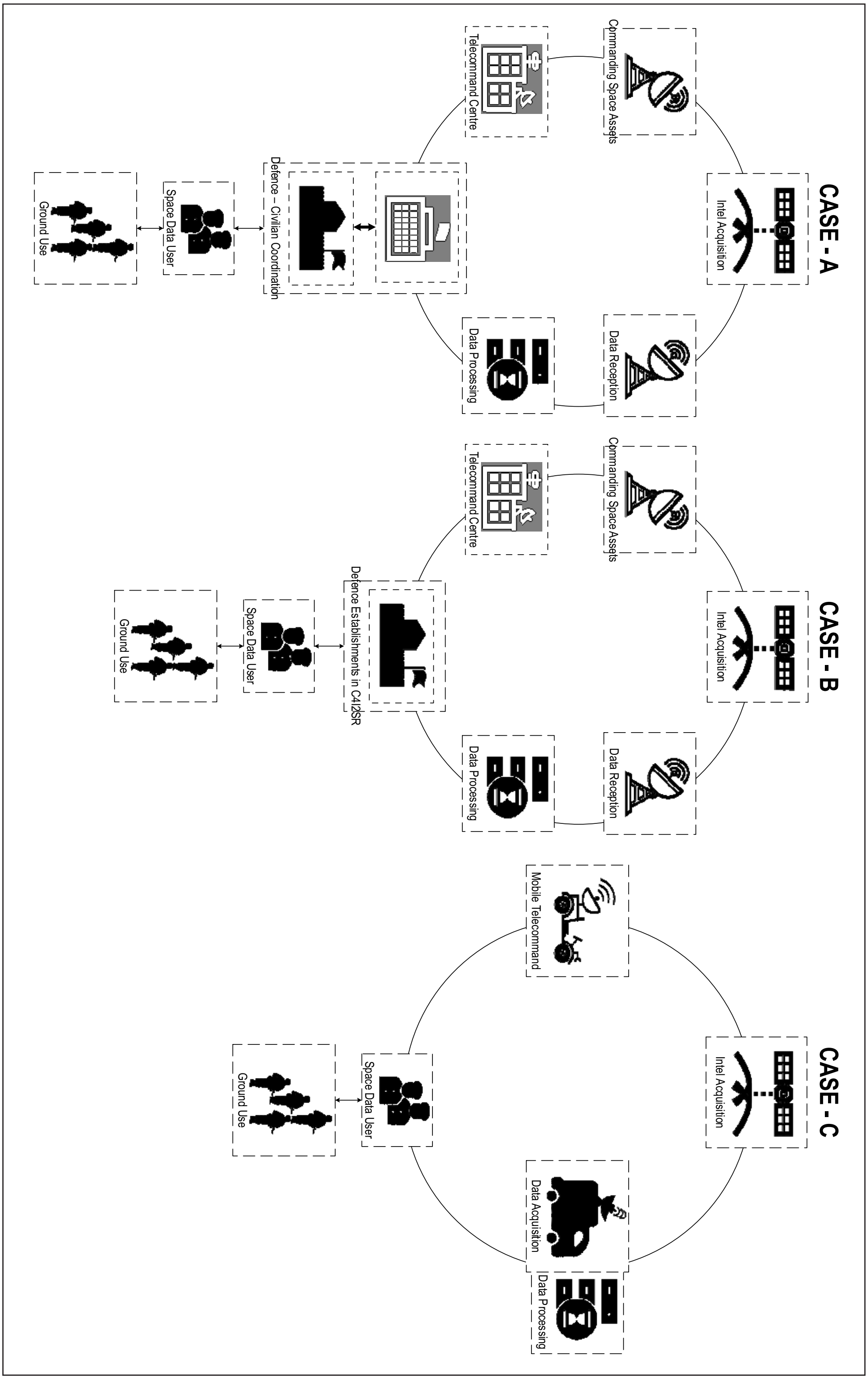
A specific example of this may be that satellites that may be commanded by the National Technical Research Organisation (NTRO) in coordination with the armed forces tasking and specially cater to the their requests, while another organisation Defence Image Processing and Analysis Centre (DIPAC) with receiving centre at Gwalior supporting the armed forces by analysing satellite data.[75] Although the operational regime of such a system may lie completely within the defence establishments' ambit, this is also a case of increased latency of generation and processing of intelligence and eventual use.

Case C

It is important to note that the rapid rise of miniaturised technology has not only resulted in developing smaller space assets but also has made a case for using potentially mobile ground segments that can receive data at unprecedented rates and can be processed in near-real time for facilitating the intelligence needs specific to a user. Some of the particular users within the C4I2SR realm can benefit from specifically tailored technology architectures that shall enable direct real-time relay of intelligence for decision-makers at a particular area of interest to directly act on the intelligence.

Extension of this tailored technology architectures into space assets for specific space data users within the C4I2SR based on the applications needed within particular areas of interests provides an excellent opportunity to create a closed loop of direct access to space-based assets to a particular post or user, therefore providing a near-real time capability. This is one of the best plausible scenarios of low latency operations within least hops in the chain of actions required in gathering, processing and choosing to act on intelligence.

Figure 1: Space-based C4I2SR Decision Models[76]



A typical geo-intelligence example of such an operational regime can well be to have mobile ground segments that can be used to command the satellites to specifically image particular areas of interest while the gathered data is directly relayed to a particular post or user (also using mobile ground segments) who is in need of such intelligence. The mobile segment on the user or post may have an integrated data processing unit that specifically caters to the signatures and analytics that are of interest to the user. Some of these aspects of utility in C4I2SR concern the ability to tailor technology architectures to suit such low-latency decision-making approaches. An extension of such can move into specific geo-coordinates may be marked for automatic intelligence acquisition and relay with archival mapping.

The current form of space-based C4I2SR in India can well be a mix of both Case A and Case B depending on the type of intelligence. However, with the maturity of technology alongside miniaturisation, reliability, constellation capabilities, there lies a strong case for defence forces to consider moving to an independent, low-latency, tailored architecture regime (Case C) to facilitate near-real time operations with space-based C4I2SR.

Responsive launch

The assembly line model when applied to small satellites can provide capabilities to launch swarms of satellites with specific capabilities in short time spans depending on the C4I2SR requirements. With the low-cost, low-life design approach these swarms can be put up into LEO with specific mission timelines of a year or less to provision rapid intelligence gathering capability. Using LEO such as 300 km can serve to such operations. These mission architectures also allow for specific missions in geo-intelligence (especially in imagery) to use much smaller payloads (cameras/lens systems) and make a case for a swarm of small satellite systems that can be built in timelines of less than four weeks. The key to such operations shall be the compensation in temporal resolution of intelligence.

In order to gain such operational capability, launch on demand of such swarm systems is a key enabler.With ISRO's workhorse Polar Satellite

Launch Vehicle (PSLV), taking time of about 45-60 days in assembling for a launch[77] (mainly due to its configuration as a satellite launch vehicle). With only two launch pads operationally available with the third under consideration,[78] India has a limited satellite launch capability for rapid responsein putting up space assets. The Inter-Continental Ballistic Missile (ICBM) programme of the country can be leveraged as a solution to operationalising launch on demand capability.

As the country's missile program is gaining momentum with the success of Agni-V and the progressive development of longer range missiles, there is core technology foundation available within the defence establishment to augment the ICBM capabilities to turn them into satellite launch vehicles. According to former Defence Research and Development Organisation (DRDO) Chief VK Saraswat, Agni 5 does have the capability of launching military satellites on demand.[79] However, no such known tests have been performed so far.

The conversion of ICBMs into satellite launch vehicles has a history with examples such as the American Atlas and Titan families starting their life as ICBM programmes, and their modified versions being used as space launch vehicles.[80] Similarly the Russians have the DNEPR launch programme with the first and second stage of the original SS-18 ICBM used with a modified third stage control system flight software capable of delivering over 2-tonne payloads to 500 km 98o circular orbits.[81] In one of the recent DNEPR launches in 2014, the rocket put a record 37 satellites into orbit.[82]

One of the distinctive feature addition to the utilisation of the Agni-V has been its “canisterisation”. This allows the missile to be mounted on a flatbed truck thereby facilitating the transport of it into a launch site for firing it on-demand (by hydraulically raising the canister into the vertical firing position). With the recent successful test of the canister-based launch,[83] there is tremendous scope to leverage the ability of launch on demand for small satellites using the Agni-V variants.

Once a responsive launch capability is built, it gives the ability to integrate rapid deployment of satellites, commanding stations as a part of a rapid response programme for tactical scenarios. There seems to be less of technology gap and more a policy gap to make such programmatic decisions in the country.

DEFENCE INNOVATION POLICY

While Government of India programmes such as 'Make in India' are relevant for closing the gap in defence production and intellectual property within the country, one of the key issues in development of a strong indigenous defence industry in India with the promotion of indigenous technology includes the mechanisms of promotion and development of small businesses, especially startups.

Although strides have been made by publishing white papers such as the Technology Perspective And Capability Roadmap (TPCR) 'to establish a level playing field for the Indian defence industry, both public sector and private industry' and 'to provide the industry an overview of the direction in which the Armed Forces intend to head in terms of capability over the next 15 years, which in turn would drive the technology in the developmental process',[84] without an active promotion and incentivised technology development roadmap within the country by small businesses, the country may still have to remain a large-scale importer of products and services.

The United States Department of Defense (DoD) Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Program is an excellent example of helping entrepreneurs in the defence sector to materialise state-of-the-art technology starting from the conception stage through to the technology development and subsequent commercialisation.

The DoD issues three SBIR and two STTR solicitations for proposals annually[85] which get evaluated for grants. The proposals solicit the total price, including profit being proposed typically run in the following three Phases:

- Phase I includes the determination of the scientific, technical, and commercial merit of the ideas submitted. The Phase I award is usually limited to $150,000 over a period of six months.
- Phase II is the technology development leg where major research and development is funded to develop projects into technology to

support the needs of warfare. The Phase II is usually limited to $1 million and usually span 24 months.

- Based on the success of Phase II, Phase III kicks off with the commercialisation into a product or service for the government and commercial marketplace. Small businesses are expected to obtain non-SBIR government or private funding to transition Phase II technologies.[86]

According to statistics published by the US DoD SBIR/STTR programme, $1 billion in research fund is being awarded annually. Out of the 2,500 proposals that are awarded, 25 percent are given to first-time winners, 50 percent are to firms with fewer than 25 people, 33 percent are to firms with fewer than 10 people, 20 percent to minority or women-owned businesses. The total revenue generated in commercialised technologies is estimated at$31 billion.[87]

The inclusion of grants for startups under the extramural R&D budget of the armed forces and defence agencies can accelerate the development of technology by small teams of innovative entrepreneurs. The phased release of these grants on a similar line of SBIR can create a lot of worth in IP development within the country in the private sector ecosystem.

CONCLUSIONS AND RECOMMENDATIONS

Developing operationally responsive small satellites to explore space security interests of India is an important dimension to be explored. The planned creation of a defence space agency must look at how small satellites can complement legacy systems within the country to provide effective space-based services to the armed forces.

Expansion into using space-based systems for space security provides an excellent opportunity for the greater integration of Indian private industry into the defence ecosystem. However, small satellites are just one facet of enabling tactical users to take advantage of space.

Small satellites can provide complementary capability to larger systems such as CARTOSAT and provide excellent revisit and experimental capabilities. One has to note that operational responsiveness is an important concept for future tactical warfare. In the context of small satellites, operational responsiveness can only be fully capable by building responsive launchers, responsive ranges and responsive command & control, tasking, processing, exploitation & dissemination.

From a techno-entrepreneurial perspective, some of the key lessons for the development of a strong defence innovation within India include the following:

- Small businesses, especially startups, cannot work under the umbrella of possible procurement of a turnkey solution in a decade. Given the current organisational structure of defence technology development and procurement, there is a need to find innovative ways of integration of Defence Public Sector Units (DPSUs) and other key defence agencies to encourage startup companies, right from initiation of technology conception to commercialisation of the technology at a turnkey level.
- One of the key issues in technology development and eventual commercialisation is the maturity of the mechanisms of technology transfer, sharing of government infrastructure, development of state-of-the-art facilities (especially for electronics) for novel technology development that can be rented by startups (since most of them are bootstrapped).
- Transparent solicitation of information on grant programmes within the country across defence verticals as an effort of creating an environment of 'Ease of doing Business' in the defence sector. A single portal for federal defence funding for small businesses may be developed to encourage information dissemination (schemes, timelines, formats, and results) to entrepreneurs in the private sector. ORF

ABBREVIATIONS

ADS-B	Automatic Dependent Surveillance–Broadcast
AIS	Automatic Identification of Ships
AFRL	Air Force Research Laboratory
ALASA	Airborne Launch Assist Space Access
AoI	Area of Interest
ARTEMES	Advanced Responsive Tactically-Effective Military Imaging Spectrometer
ASAT	Anti-Satellite
ASIC	Application-Specific Integrated Circuits
ASIM	Appliqué Sensor Interface Module
C4ISR	Command, Control, Communications, Computers, Intelligence, Information, Surveillance, and Reconnaissance
CHAMPS	CubeSat High-Impulse Adaptable Modular Propulsion System
CHIPS	CubeSat High Impulse Propulsion System
CIA	Central Intelligence Agency
CNES	French Space Agency
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COTS	Commercial Off The Shelf
DARPA	Defense Advanced Research Projects Agency
DIA	Defense Intelligence Agency
DIPAC	Defence Image Processing and Analysis Centre
DLR	German Space Agency
DGLL	Directorate General of Lighthouses and Lightships
DHS	Department of Homeland Security
DPSK	Differential Phase Shift Keying

DPSU	Defence Public Sector Units
DRDP	Defence Research and Development Organisation
DoD	Department of Defense
ECAPS	Ecological Advanced Propulsion Systems
ELINT	Electronic intelligence
ELISA	ELectronic Intelligence by SAtellite
EO	Earth Observation
ESA	European Space Agency
FDM	Fused Deposition Modelling
GEO	Geostationary Earth Orbit
HAP	High Altitude Platforms
HPGP	High Performance Green Propulsion
ICE-Cap	Integrated Communication Extension Capability
ICBM	Inter-Continental Ballistic Missile
IMS	Indian Mini Satellite
ITU	International Telecommunications Union
LCRD	Laser Communications Relay Demonstration Project
LCT	Laser Communication Terminal
LEO	Low Earth Orbit
LOLA	Liaison Optique Laser Aéroportée
LRIT	Long Range Identification and Tracking Systems
ISRO	Indian Space Research Organsiation
MUOS	Mobile User Objective System
NAIS	National Automatic Identification System
NICT	National Institute of Information and Communications Technology
NRO	National Reconnaissance Office

NTRO	National Technical Research Organisation
OGS	Optical Ground Station
OPALS	Optical PAyload for Lasercomm Science
ORS	Operationally Responsive Space
OSIRIS	Optical Space Infrared Downlink System
PAN	Panchromatic
PnPSats	Plug-and-Play satellites
PPM	Pulse Position Modulation
PSLV	Polar Satellite Launch Vehicle
RF	Radio Frequency
SAR	Synthetic Aperture Radar
SAO	Survivability Assurance Office
SBIR	Small Business Innovation Research
SEM	Space Environmental Monitoring
SENSE	Space Environmental NanoSatellite Experiment
SMV-STP	Space and Missile Center's Space Test Program
SMDC	Space and Missile Defense Command
SNaP	Nanosatellite Program
SOCRATES	Space Optical Communication Research Advanced Technology Satellite
SOTA	Small Optical Transponder
SPA	Space Plug-and-Play Avionics
SPAWAR	Space and Naval Warfare Systems Command
SSC	Swedish Space Corporation
SSTL	Surrey Satellite Technology Ltd
SSTP	Small Spacecraft Technology Program
STTR	Small Business Technology Transfer

TACSAT	Tactical Satellite
TEC	Total Electron Content
TPCR	Technology Perspective and Capability Roadmap
UAV	Unmanned Aerial Vehicles
USSOCOM	U.S. Special Operations Command
VTS	Vessel Traffic Services
WSN	Wireless Sensor Network

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