Thinking Outside the "Cube"

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Small satellites have become attractive tools for diverse space mission applications. Groups of small satellites are well-placed to address applications that require global coverage or high temporal resolution, which cannot be achieved with an individual satellite. CubeSat standard formats and interfaces have made it easier to develop small spacecraft, and encouraged the creation of an ecosystem of companies providing technologies and services. This has stimulated a rapid growth in the number of "Owner-Operator" organisations that intend to develop commercial services in communications, Earth Observation and other areas.

Previous programs have shown that users tend to demand greater capability once basic capabilities have matured. Historical data indicates that 50kg-class microsatellites designed in the 1990's formed the basis for a large number of 80-150kg spacecraft missions in the 2000's. Similarly, we now expect advances in CubeSat technologies to lead to demand for more capable nanosatellites; we have already seen 1U CubeSats being overtaken by 3U CubeSats, and 6U, 12U and even larger "CubeSats" emerging.

There is now a large user base for CubeSats, driven by demand from academic, institutional and commercial customers to fly larger, more complex payloads, underpinned by a robust, reliable spacecraft bus that can deliver longer mission lifetimes. However this community has become accustomed to the CubeSat design standards, pricing and schedule philosophies. This paper provides an overview of the Nanosatellite market, and describes a nanosatellite bus which applies such CubeSat approaches to larger, scalable nanosatellites. This increases mission value, and supports more demanding payloads which cannot be easily accommodated in a CubeSat format in an affordable manner.

This paper presents example mission architectures as well as current SSTL missions to illustrate how increasing the mass and volume of a nanosatellite can provide substantially higher return on investment in science or commercial terms.

Key Words: CoreDHS, CubeSat, Nanosatellite, Small Satellite, Scalable, System Engineering

1. Introduction

1.1. CubeSat capability, utility and purpose

CubeSats play a vital role in the space industry, offering low-cost demonstrations and proof-of-concept missions; and in some cases, commercial operators have been able to make very successful businesses with them. The popularity of the CubeSat has been rapidly increasing over the past few years; from humble beginnings it is now frequently considered as a possible baseline for large multi-satellite constellations or for complex technology demonstrations. Technology in the past three decades since SSTL was founded has significantly improved, with faster processors, larger data storage and miniaturised sensors and actuators all capable of fitting within much smaller volumes than before.

CubeSats have been a disruptive force in the satellite industry; technology improvements increasing the utility of progressively smaller spacecraft, increasing acceptance of the relevance and use of CubeSats, and the growth in demand for applications that can be delivered with multiples of identical, volume-manufactured spacecraft are contributing factors to this trend.

CubeSats have played an important role in increasing accessibility to space for organisations with fairly simple mission objectives that can be achieved for a relatively small budget. They have also played a part in driving technology developments to improve the capability of cubesats within the significant payload accommodation and power generation constraints imposed by the restricted cubesat dimensions and form factor.

Whilst the CubeSat form factor has been a catalyst for technology and miniaturisation innovations, the CubeSat form factor does result in some design limitations, such as payload accommodation constraints and limited downlink capability. The limitations on solar array area and battery accommodation volume drive the mission operational capability, and generally, because of the size and separation limitations for accommodating AOCS actuators and sensors, there is a ceiling on the pointing knowledge and accuracy that can be achieved.

Startup companies with small balance sheets - and established operators wishing to limit their risk exposure - find the low "cost of entry" of cubesats appealing and are often willing to relax their mission requirements and objectives as long as a reduced mission can be done within the available budget.

It is accepted that CubeSats are useful tools for the initial validation of technologies and mission concepts, however it is also acknowledged that cubesats are not able to meet the wide-ranging mission demands of most modern demonstrator and operational payloads. Cubesats are not able to physically accommodate such payloads, or provide the power necessary to operate them. Cubesats are also not well-suited for operational missions requiring longer lifetimes in higher orbits, large volumes of propellant, improved payload accommodation and mission performance, and missions which rely on a higher likelihood of mission success. Such limitations generally make it difficult to leverage CubeSats to close a financial business case for sustainable commercial operations.

1.2. Small satellites for sustainable business models

SSTL was one of the first providers of small satellites for institutional and commercial missions, and has both witnessed and leveraged the evolution of technology and reduction in form factors across the whole range of spacecraft avionics.

With the increasing popularity in CubeSat missions and constellations, many of SSTL's customers are seeking an alternative to CubeSat platforms. While CubeSats are inexpensive (in real terms) to launch, many fail in orbit or re-enter the atmosphere after a short operational duration, which can make it difficult to rely on them to generate sustainable revenues.

Customer platform requirements typically include: the need to operate reasonably-sized payloads with moderate power demands, large on-board data storage capacity, high dV propulsion, high speed downlinks and/or inter-satellite links. Another important criteria is the need for reliability, with robust FDIR (Failure Detection, Isolation and Recovery) and safety features enabling mission lifetimes of at least five years in LEO to facilitate a sufficient return on investment and a path to profitability.

These spacecraft platform needs are extremely challenging to achieve in a CubeSat form factor – particularly in relation to batteries, solar cells and propellant as these can only be reduced to a finite size. While new technologies are on the horizon for higher density batteries and quadruple (and even quintuple) junction solar cells, these are still relatively immature and have other limitations (such as some of the higher capacity batteries having reduced performance on longer mission lifetimes).

SSTL has evaluated these market requirements to determine the optimum set of capabilities needed in a microsatellite – for a cost that is comparable to a cubesat – such as:

- A longer lifetime (five to seven years)
- Significantly increased power generation
- Significantly increase power storage
- Capability for higher power in-eclipse operations
- High payload mass fraction and volume fraction
- Better AOCS knowledge, stability and agility
- Propulsion options from station-keeping to constellation phasing and orbit raising

A key factor necessary to successfully achieve this approach is ensuring that the spacecraft design, manufacture, launch and total mission costs are low enough to enable profitability over the mission lifetime. With CubeSat lifetimes of one to two years on average, the replenishment costs associated with procuring, launching and commissioning up to seven CubeSats is likely to exceed the cost of procuring, launching and commissioning one single, more capable, satellite that has been designed for a mission lifetime of seven years.

1.3. The answer is 42

Rather than defining a single platform that can address all of these requirements inefficiently, SSTL characterised the customers' needs to determine a common suite of configurable avionics upon which a number of standard and customised satellite platforms can be built.

This is the philosophy behind the SSTL-42: a set of avionics optimised for the sub-100kg platform class, with smaller form factors, units with common functionality combined into single units, and a highly capable power subsystem.

The following sections provide a description of the SSTL-42 avionics, and discusses example missions requiring different platform configurations, all based on the same common architecture.

2. Modularity, scalability and flexibility at low cost

In the highly-competitive sub 100kg platform market, there are increasingly more entrants and more products to choose from.

To ensure that SSTL continues to be at the industry forefront, innovative solutions have been implemented into the satellite avionics – all of which maximise the benefits to our customers of 30+ years of heritage and experience in this market.

These key innovations include reducing the number of physical units on board by combining core functions into single units – making much more efficient on-board data handling, AOCS and on-board data storage. They also include advancement of SSTL's core units for smaller form factors so that power and propulsion subsystems are highly optimised for very high power and dV operations in a nanosatellite form factor.

In solidifying these innovations into a single avionics baseline for all sub-100kg LEO platforms, SSTL can provide an "off-the-shelf" low-cost approach to platform design and manufacture – but with the significant added benefit that the core system is designed, manufactured, tested and operated by the same engineers throughout its lifetime. The engineers have an intimate knowledge of the units on board, which allows for a rapid assembly and a highly efficient ground test campaign and in-orbit support and knowledge.

The SSTL-42 avionics and their corresponding platforms all benefit from SSTL's standard reliability, redundancy and FDIR approaches – with the same technology being utilised on SSTL's larger LEO missions, simply size-optimised for these larger missions. This offers customers confidence in the platforms and satellites produced in this class, and low-risk transitions for future missions between platform sizes within the SSTL LEO platform portfolio.

2.1. Highly capable, payload-optimised platforms

SSTL's standard <100kg platforms utilising the SSTL-42 avionics can be tailored for simple and well considered payload interfaces for a range of payload types. Focusing on the core payload needs (power provision, thermal management, mechanical accommodation, data interfaces, FDIR and safety), each standard platform focuses on providing these in a highly optimised way, to reduce the platform mass, cost and volume as much as possible.

Initial platform designs support the following variants (Figure 1):

	Payload	OAP	Mounting	Mechanical
Standard Power	Any (including multi-payload)	>15 W (always on)	Flat mounting plate	Up to 75 kg payload 55 x 55 x ~60 cm
High Power	Any (including multi-payload)	>80 W (always on)	Flat mounting plate	Up to 75 kg payload 55 x 55 x ~60 cm

Figure 1: SSTL-42-based standard platforms are tailored for payload and mission operations requiring high power provision, even in eclipse. Platforms can provide tailored thermal management schemes to support the payload operations accordingly.

The key differentiator for these platforms is a very high payload mass and volume fraction and the array configuration – which can be tailored for all the orbit altitude and inclination, to provide optimised power generation (Figure 2). There is also an optional upgrade to the arrays which allows 1-axis sun tracking and an additional 25% power generation. Battery capacity can also be upgraded to significantly enhance in-eclipse operations and/or to support high power short-duration operations in sunlight.

The platforms provide a flat mounting surface, for customisation to payload needs – including multi-payload demonstration missions or a single larger payload. This approach provides a good isolation between the platform and payload meaning that many different types of payload can be accommodated on the same platform. The payload panel is supported by a modular avionics stack provides. This provides the main structural support for the SSTL-42 spacecraft, which helps to minimise the platform's structural mass, a technique that has proved successful on several of SSTL's previous platforms.

The structure will be subjected to inertia, vibration and acoustic loads from the launch vehicle, shock from separation, thermos-elastic distortion during service and micro-vibrations from wheel operation. These structures are designed to survive these loads and to only impart acceptable loads on the payload and equipment.

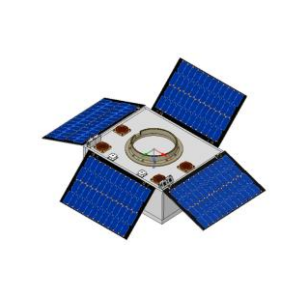
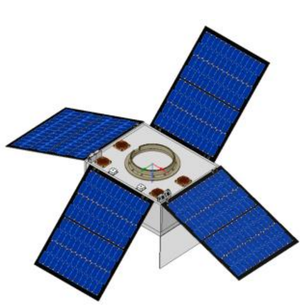
Standard Power Variant	High Power Variant
	
	
<40kg platform	<50kg platform
Payload OAP >15 W continuous	Payload OAP >80W continuous
25% power increase possible with 1-axis tracking arrays	25% power increase possible with 1-axis tracking arrays
Compatible with 500 – 800 km altitude orbits	
Compatible with a wide range of launchers, including PSLV, Falcon-9, Falcon Heavy, Soyuz	
S-Band Uplink 19.2 kbps	
S-Band TTC Downlink 38.4 kbps S-Band Payload Downlink 4 Mbps	
X-Band Payload Downlink 400 Mbps	
Payload Data Storage 256 Gbyte	
Dedicated payload radiator	
Up to 75 kg payload mass	
Reliable, accurate AOCS, optional upgrade to include star tracker	

Figure 2: The SSTL-42 avionics has initially been implemented into two platform form factors – tailored for payload power generation needs.

3. SSTL-42 standardised avionics – overview and key features

The SSTL-42 avionics are designed to operate below 800 km for mission lifetimes of five to seven years. Whilst the baseline platform configurations and performance parameters assume inclinations above 50 degrees, these baselines can be tailored to address mission-specific needs. Future work will also look at the addressing higher LEO altitudes.

Systems based on the SSTL-42 avionics all benefit from the highly integrated, optimised and standardised approach described in the previous section, which allows for a standardised, robust FDIR and safety approach across the entire LEO range. As a result, software requires less tailoring for each mission – reducing complexity and test campaign times accordingly to improve spacecraft prices and schedules – and also enabling customers to leverage and build upon prior investments from previous SSTL missions

The SSTL-42 avionics suite is production engineered for automated manufacture and test, which allows additional cost and schedule savings to be realised when manufactured in batches for deploying an operational constellation.

This core set of avionics performs all of the functional roles common to the vast majority of missions in LEO. However, the platform can be further augmented, on a case by case basis, with additional and/or higher performance subsystems.

3.1. CoreDHS

The backbone of the SSTL-42 avionics, is the Core Data Handling System (CoreDHS), which brings the functionality of the On Board Data Handling (OBDH) subsystem, Attitude and Orbit Control Systems (AOCS) subsystem and the RF Telemetry and Telecommand (TTC) uplink and downlink communication subsystems into a single unit (Figure 3).

This results in a more efficient system, by directly connecting the systems within the CoreDHS, rather than using the CAN bus. This design evolution brings all of the functional elements into a single unit, with no bus to connect between them – making some critical functions like AOCS processing much faster. The system's FDIR is adapted from knowledge and experience of SSTL's heritage systems, tailored for the way these elements interact in this up-to-date configuration.

The CoreDHS is a dual redundant system with a compact footprint, relatively low power consumption when compared to traditional avionics systems with comparable capability and functionality.

Two CoreDHS units act as the primary and cold redundant flight computers and are responsible for the control of the platform and payload. They run all the critical on-board flight software to maintain platform and payload health, schedule mission tasks, as well as execute and monitor all AOCS operations.. Each unit contains its own S-band transmitter and receiver, GPS receiver and AOCS controller. This approach provides redundancy for mission robustness and resiliency.

The CoreDHS can support a number of different payload interfaces. The unit runs software tasks on board to monitor the health of spacecraft, including a dedicated payload task.

The primary On Board Computer (OBC) and AOCS interface functions are implemented on a LEON3 processor with a Xilinx Zynq co-processor. Any software requiring mission-specific high-end processing are handled through this Xilinx Zynq processor.

3.2. Payload Data Storage - Optional

Data storage for the payload is provided through the Payload Chain Card – which offers 256 Gbyte (expandable) memory for payload data and an interface to the X-Band downlink chain for high speed downlink.

Figure 3: A single dual-redundant CoreDHS board - Rev. A

3.3. Communications

3.3.1. Telemetry and Telecommand (TTC)

Physically located on the CoreDHS units, the TTC subsystem operates in the standard spacecraft operations bands at S-band, and enables ground-based operators to monitor and control the functions and behaviour of the satellite through telecommands and telemetry.

Antennas are placed on different sides of the spacecraft in order to support both the early phases of the mission, safe mode, and nominal mode operations. This configuration provides robust means to operate the spacecraft in any orientation, or possible tumble for when it is initially deployed from the launcher.

3.3.2. S-Band payload operations

The standard spacecraft operation bands at S-band allows the spacecraft to be operated from a wide range of ground stations around the world, in addition to the SSTL-owned ground network. Data rates achievable from the S-Band transmitter in the CoreDHS, at up to 4 Mbps, are sufficient to support payload data downlink on missions with low to moderate data downlink requirement.

3.3.3. X-Band Downlink - Optional

An X-Band transmitter, with several antenna options, is an optional upgrade, providing up to 400 Mbps of downlink capability for payload data. Accommodated in the payload bay, the configuration allows early testing of the payload chain before integration with the spacecraft.

3.4. AOCS

The AOCS system ensures the required platform stability and pointing are achieved. Four sun sensors, and two three-axis magnetometers provide robust, redundant attitude knowledge on a continuous basis. Coarse Pointing Mode (CPM) provides three-axis inertial pointing using sun sensor and magnetometer measurements for attitude estimation and reaction wheels for actuation. The torque rods are used in this mode for momentum offload from the wheels. This mode maintains pointing control accuracy in sunlight.

Fine Pointing Mode (FPM) incorporates orbit determination by the GPS, gyros and optional high accuracy attitude determination by the star tracker.

3.5. Power Subsystem

The power sub system performs the following main functions:

- Generation of electrical power via solar panels
- Storage of power via batteries for use when solar power is insufficient
- Conversion of voltage and power between the solar panels and battery
- Distribution of battery voltage power to platform and payload modules

The main power system elements are:

- Power Distribution Module (PDM),
- Battery Charge Module (BCM),
- Battery,
- Hold Down and Release Mechanism (HDRM) and
- Solar panels.

3.5.1. PDM and BCM

The PDM and BCM have been designed to each fit within a half tray in the module stack (Figure **4**). These have been reduced in size by 50% from SSTL's standard power systems, by optimising them for the power needs of sub-100kg platforms.

The SSTL-42 PDM is tailored to provide a more optimised number of switches for a standard microsat-type platform, but is directly interchangeable and / or expandable with the larger heritage PDM-60, which provides an expansion of up to 60 switches in a full module tray form factor. This gives flexibility to easily adapt the design to the needs of the payloads on board.

The SSTL-42 BCM similarly has a reduced power handling capacity, optimised to the performance range of the SSTL-42 platform, and a reduced number of Battery Charge Regulators (BCRs) to reflect the smaller form factor of the microsat platform's arrays – however is again directly interchangeable with SSTL's heritage BCM150-FR.

3.5.2. Batteries

A key enabler to the SSTL-42-based platforms is the option for larger battery capacity (<40Ah) – which enables significantly enhanced short-term peak and in-eclipse operations when compared to almost all other platforms in the sub-100kg class. For mass optimisation, a smaller battery option (<20Ah) is also available for less demanding missions.

3.5.3. Solar Panels

The SSTL-42 solar panel configuration baseline is four deployable panels (+/-X and +/-Y), deployed to an angle best suited for power generation in a sun synchronous orbit. However, the angles of these panels can be tailored during manufacture to optimise power generation in the selected orbit, and there is also the option to add 1-axis sun-tracking arrays to increase power generation efficiency by around 25%.

The low mass design of the panels makes use of several technologies demonstrated on the Carbonite-2 mission.

3.5.4. HDRMs and Hinges

Lightweight and low volume HDRMs and motorised hinges have been developed by SSTL through the Carbonite programme (Carb-1 and Carb-2) and are optimised for the SSTL-42 avionics based on the envelope requirements of the payload-optimised platform baselines. Motorised hinges are optional, and it is possible to have instead a fixed angle tailored to the mission orbit inclination and altitude.

Figure 4**:** SSTL heritage Power Distribution and Battery Charge Modules (Rev.A) are optimised for microsat missions by each reducing into a half microtray volume, resulting in much more power and mass efficient units for the SSTL-42 avionics.

3.6. Propulsion systems - Optional

Several propulsion system options are available, depending on the mission-specific requirements.

The "warm gas" butane propulsion system is based on repackaging SSTL's heritage propulsion system. The propulsion system uses the SSTL Low-Power Resistojet to augment the specific impulse performance. This propulsion system achieves a specific impulse of 100s. This provides the necessary delta-V for orbit manoeuvres and maintenance throughout the mission life, including de-orbit operations.

Xenon, HTP, hydrazine and electric propulsion systems can also be included to allow the spacecraft to be tailored to address mission-specific drivers such as low-altitude missions, constellation phasing, orbit-raising and de-orbit. A target of <180m/s for a 50kg spacecraft can be achieved in the microsatellite form factor with the appropriate hydrazine or electric systems.

4. SSTL-42 mission capability examples

The platform and avionics modularity and flexibility allows SSTL's <100kg range to be configured to meet a diverse range of mission objectives and applications for single spacecraft or constellations, including:

- Technology demonstration
- Communications (RF and optical)
- Change detection
- Earth Observation (optical, IR and SAR)
- Earth weather (Reflectometry, radio occultation, atmospheric soundings)
- Science
- Space weather
- Space situational awareness

The AOCS suites allow for mission tailoring to provide highly stable or highly agile missions – depending on the needs of the payloads on board. SSTL's imaging mission heritage has been brought into the definition of the SSTL-42 AOCS suite, to ensure that the performance is market-leading for the class of platform.

Mission-specific operational needs will drive the selection of the data storage and X-Band systems. These payload chain units are accommodated in the Payload Bay, to allow for mission specific tailoring and testing of the payload chain before platform integration. These options can be provided by SSTL-supplied units or by the payload provider.

4.1. Standard Power Variant Platform

The design of the "Standard Power Variant" (Figure **5**) utilising the SSTL-42 avionics was driven by SSTL's own need to provide a flexible, low-cost option for a diversity of missions; from small "entry-level" technology demonstration missions that provide meaningful results for validation of new space technology and applications, through to operational commercial missions that are required to deliver long-term, reliable performance. A critical factor in realising these goals and the target recurrent prices is the development of a stable and flexible baseline system that can be manufactured in SSTL's production manufacturing facilities. This enables SSTL to leverage "design for manufacture" capabilities to maintain a price-competitive system that can meet a wide variety of mission requirements.

SSTL-42 Standard Power Variant

Typical applications:

- Low cost technology demonstrator
- Smaller commercial or scientific payloads
- Low resolution imaging
- Small constellations

Figure 5**:** The Standard Power Variant platform is tailored for payloads with more modest power needs, including dedicated radiator and compact form factors.

The Standard model, which has a platform mass of less than 40kg, offering significantly more capability than a CubeSat and more flexibility for instrumentation and payload accommodation. Compared to CubeSat offerings, this platform offers improved mission performance in the form of reliability, more capability and longer lifetime to meet end-user and customer performance and financial criteria.

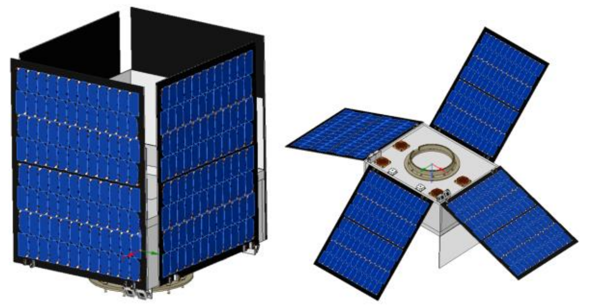
4.2. High Power Variant Platform

The design of the "High Power Variant" (Figure **6**), utilising the SSTL-42 avionics, was developed to reflect the growing need for missions to support "Internet of Things" and LEO communications businesses; requiring always-on platforms supporting payloads with relatively high power demands even in eclipse. These payloads are typically operated continuously, and the reliability of the SSTL-42 avionics becomes a significant asset in this case – supporting the mission availability and security.

This platform variant is also very well suited to the needs of multi-payload technology demonstration missions, where payloads require power allocations, and may need to operate unpredictably and simultaneously. A dedicated payload radiator and thermal management on the payload panel support these types of operations.

This variant also increases the power available to support more efficient propulsion systems such as electric propulsion.

SSTL-42 High-Power Variant



Typical applications:

- High duty cycle payloads
- Multi-payload missions
- Larger commercial or scientific payloads
- Higher resolution imaging
- Large constellations

Figure 6: The High Power Variant platform is tailored for payloads with more challenging power needs, including dedicated radiator and good power provision during eclipse.

This variant offers the same capability that would have previously been only offered on much larger platforms, making it an excellent value prospect for high duty cycle commercial missions and constellations.

5. Platform design for production and low cost

The SSTL-42 platform is production engineered so that the avionics can be manufactured and tested using SSTL's automated manufacturing, inspection and test equipment which has undergone several years of extensive qualification for manufacturing space hardware. This industrialisation approach increases the performance/cost ratio of the spacecraft and makes it ideal as a basis for spacecraft intended for batch manufacture.

6. Continuous innovation and performance improvement: Next-generation SSTL-42

The next generation concept for the SSTL-42 will take advantage of the further miniaturisation of avionics to allow for additional volume within the platform to be used for accommodation of payload or additional subsystems. The increase in payload volume is detailed in Figure 7: .

This central recess allows the back end of a telescope to be sunk into the platform, taking design inspiration and heritage from SSTL's Carbonite series. The internal volume can also be used for other payload units of the accommodation of propellant tanks for missions with high dV requirements.

In addition to the volumetric improvements, continued improvements in the efficiency of subsystems will result in a greater share of the total generated power available for the operation of the payload.

	Payload	OAP	Mounting	Mechanical
Standard Power	Telescope (or high dV system)	>15 W (always on)	Payload bay with central recess for internal mounting	Up to 75 kg External: 55 x 55 x ~60 cm and Internal: 20 x 20 x 20 cm
High Power	Telescope (or high dV system)	>80 W (always on)	Payload bay with central recess for internal mounting	Up to 75 kg External: 55 x 55 x ~60 cm and Internal: 20 x 20 x ~20 cm

Figure 7: Next generation SSTL-42 enhanced payload accommodation capacity

7. Conclusion

We have dedicated our long, successful history in the space industry to not only challenging cost targets, but striving to achieve a similar performance and lifetime to significantly more expensive systems. SSTL's approach to achieve this lies in combining, tailoring and tuning COTS technology to our designs, and ensuring those designs are capable and suitable for long-term operations in space. One of the reasons behind our mission success is that the company has developed and grown with each new enabling component, material and process over our 30+ years in business. A grass-roots understanding of how terrestrial technology, combined with SSTL's approach to system engineering, can and will behave in the space environment is how SSTL ensures these designs are so successful in enabling low-cost missions.

Our current design activities are focused on developing smaller, more resource-efficient systems, as the need to constrain design parameters so heavily on the very small systems drives innovation – allowing us to advance the capability and performance all of our satellites.

The SSTL-42 platform is a prime example of this approach as it yields significant increases in performance, coupled with reductions in mass, all on a solid foundation of SSTL heritage systems.

By significantly reducing mass, power consumption and volume, our next generation of satellites are increasingly allowing our customers to access lower-cost launchers and to benefit from significantly more payload volume for the same size and class of spacecraft.

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