"Satellite-as-a-service": a new approach for space industry

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Abstract. *A shared-access, single host/multi-tenant* satellite platform can dramatically lower the costs and accelerate the development schedule of many areas of space technology, particularly in the software domain. This approach can offer an ability to host multiple missions on a single spacecraft, sharing the capabilities of both the platform and payload instruments between multiple customers that can perform mission operations and experiments according to their needs. Communication, marine and aircraft tracking, astronomical and Earth observation are among the most suitable mission types for such a usage scenario. The proposed system design will use multiple safety features, using "defense-in-depth" strategy, to minimize the risk of potentially faulty third-party mission software prematurely ending satellite mission. These features will include extensive ground segment test validation facilities, isolation of user-accessible hardware from the rest of the satellite subsystems and vetting execution of user software through the supervisory satellite flight computer. Our company is proposing to launch a simple Earth observation cubesat to demonstrate feasibility of this concept and offer an opportunity to get first-hand experience at software development and mission operations in real space environment for the widest possible audience.

1. Introduction

For the purpose of this document, a “nanosatellite” is defined as either a small satellite specified in either units of 10x10x10 centimeters (also known as a “cubesat”) or using the broader definition of a “small satellite with a launch mass in the range between 1 and 50 kg”. Nanosatellite subsystem capabilities, such as power budget, communication bandwidth, computing performance and payload instrument resolution are continuously increasing in pace since the launch of the first cubesat in 2003, opening up more opportunities for wider commercial and research applications.

Modern space industry is witnessing an exponential growth in the small satellite and nanosatellite areas, with the numbers of such satellites successfully launched went from single digits annually in the years before 2008 to hundreds in 2017 and 2018, as illustrated in the chart below:

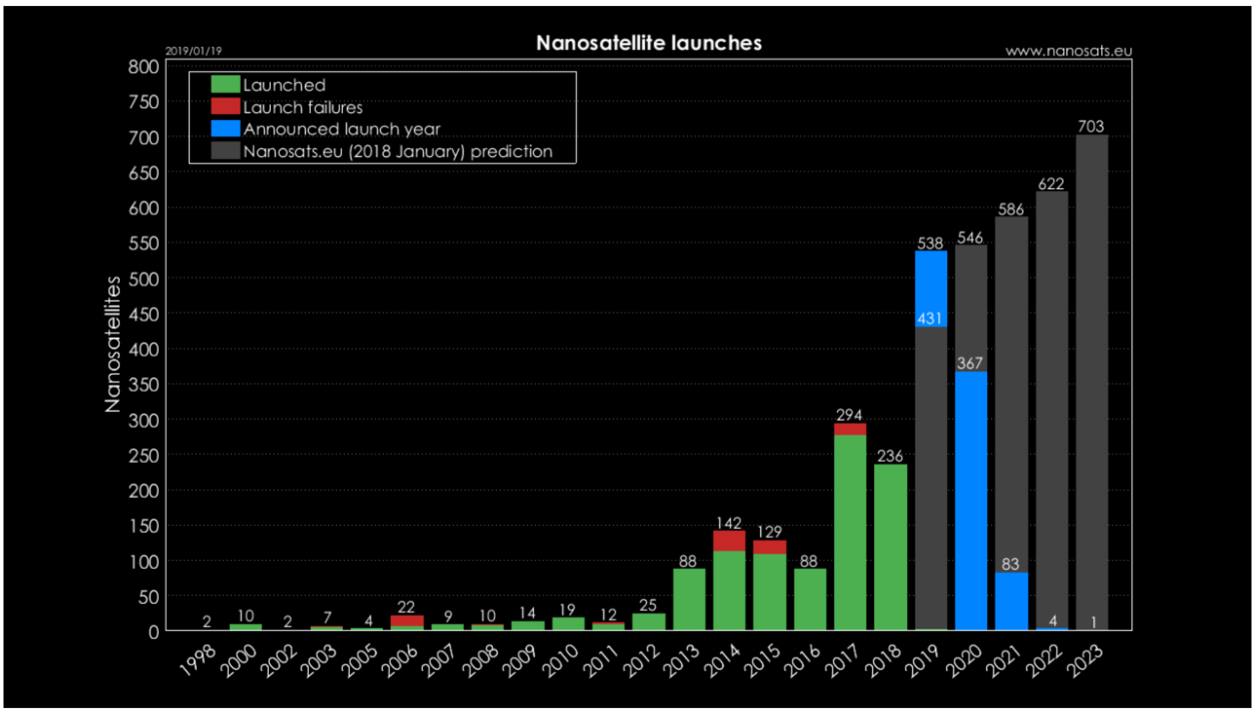


Image source: Erik Kulu, Nanosatellite & CubeSat Database, www.nanosats.eu

It might be said that the present satellite industry is experiencing its “better, faster, cheaper” moment similar to the emergence of low-cost business and personal computers in the late 1970s and early 1980s or appearance of cloud computing services in the early 2000s. These developments revolutionized the information technology industry and created the modern digital world as we know it today.

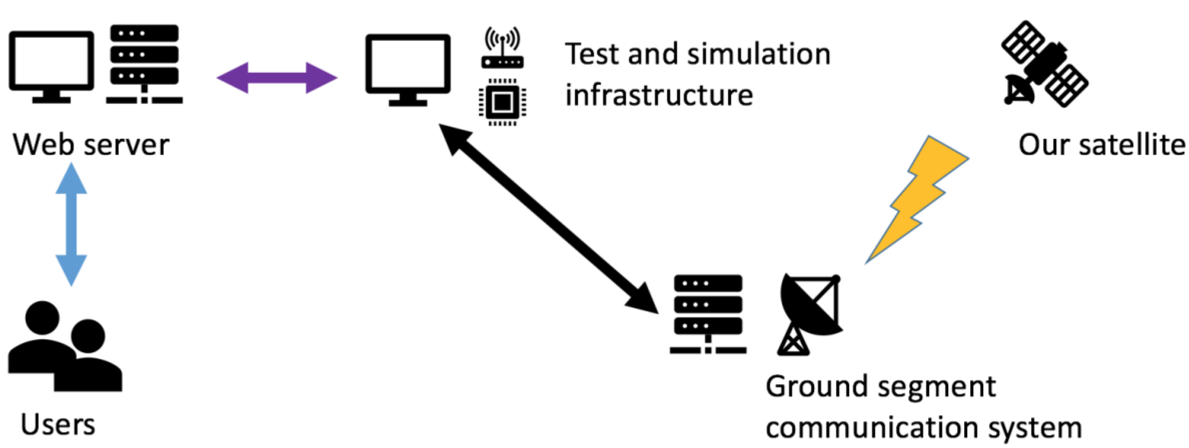
However, unlike information industry, any party willing to start satellite launch and operation activities has to deal with extensive regulations and cost barriers, limiting the growth potential of this area. One may wonder if it is possible to create an entrance into space exploration that can bypass all those barriers, using lessons learned from the evolution of terrestrial computers.

2. Concept summary

A shared-access, single host/multi-tenant satellite can dramatically lower the costs and speed up the development schedule of many areas of space technology, particularly related to software area. This approach can also offer an ability to host multiple missions on a single spacecraft, sharing the capabilities of both the platform and payload instruments between multiple customers who can perform mission operations and experiments according to their needs.

Our company, Exodus Orbitals, is planning to build and launch such a satellite with the goal of demonstrating this concept to the widest possible client base no later than Q4 2020. To minimize the risks and accelerate the technology development, this mission will be a relatively simple 3U cubesat with a visible spectrum Earth observation camera as the primary payload instrument. The expected observation performance will be around 50m/pixel, when launched into a circular Sun-synchronous orbit with 500 km altitude. The satellite capabilities will include three-axis attitude control pointing capabilities, VHF/UHF and S-band transceivers for communication of mission data and diagnostic telemetry. Photovoltaic panels fixed on the satellite frame will be used for the power generation. A preliminary design review has been completed as of April 2019 and we are preparing for the next step of our project – building the series of progressively more sophisticated hardware prototypes.

Our mission is not the first of its kind. OPS-SAT, a 3U cubesat mission from European Space Agency is expected to launch in Q4 2019 with a similar purpose of creating an in-space software development platform for third-party users. This satellite is considerably more advanced than our design, with X-band transceiver and optical communications system in addition to UHF and S-band radios, dual attitude and orbit control subsystems and deployable solar panels. However, our mission will offer an opportunity to participate for a much wider user base, not limited to ESA flight control teams. The core functionality and mode of operations are very similar for both projects, illustrated below:



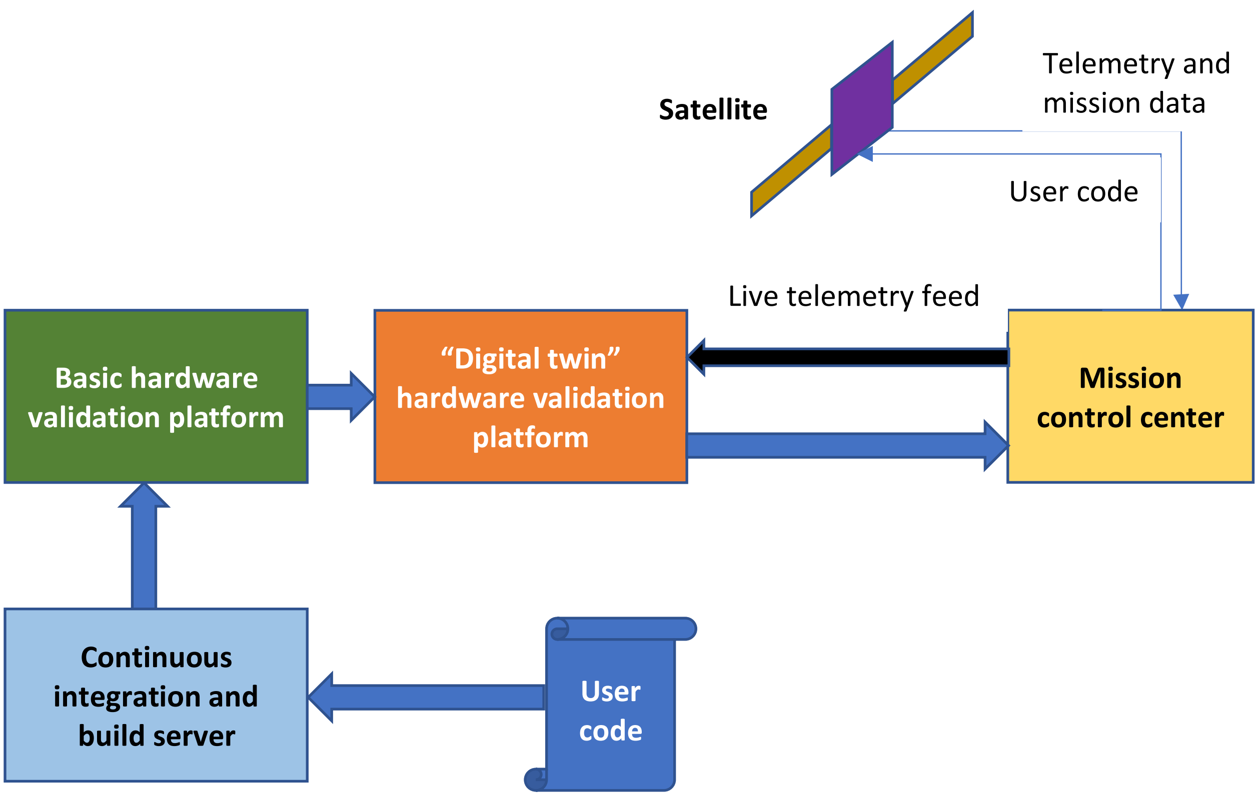
Summary of the mission design concept

2.1 Ground segment description

Availability of robust test framework and validation facilities is important to reduce potential flaws in the user applications that will be uploaded to the satellite. Industry standard validation and verification software will be used in addition to custom-designed validation tools:

- A continuous-integration development pipeline will be offered, using modern commercial and open-source source tools such as GitLab and Jenkins CI. The validation harness will include test suites that verify the software in both nominal and fault mission scenarios as well as automated estimates of the quality of submitted mission software in both performance and correctness domains, similar to the methods used for ACM and ICFP programming contests and online learning platforms such as Rosalind and Coursera.
- A two-stage validation platform will be used, a simplified "flat-sat" hardware environment to pass the basic sanity checks and a full-scale ground simulator closely matching the flight hardware, running a "digital twin" model of the satellite in orbit using a live telemetry feed. All customer code will be evaluated in both type of environments before any deployment to space, with necessary level of protection of owners' intellectual property rights.

This architecture, illustrated below, is not dramatically different from existing infrastructure used for contemporary space missions, but will be implemented using most modern software tools.

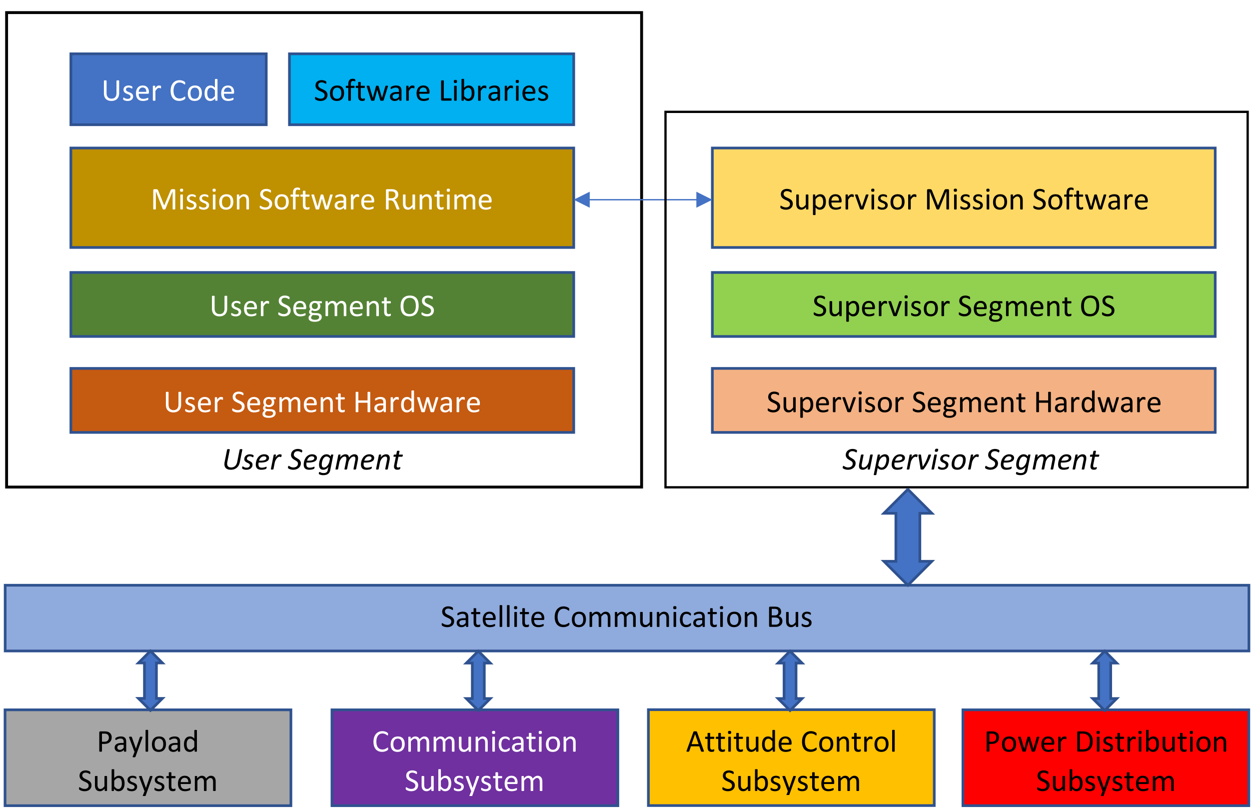


Ground segment validation and verification setup

2.2 Space segment description

Most of our first satellite subsystems will be implemented in a manner very similar to previous nanosatellites, however the design of the onboard data-handling and command system will include multiple additional precautions for both ground and space segments to minimize the risks of potentially faulty third-party mission software to be executed on our satellite platform. The summary of these precautions is given below:

- The satellite onboard data-handling and command subsystem will be split into user and supervisor segments, where customer code will run only within user segment, which will be protected "sandbox" isolated from the rest of the satellite subsystems.
- The middleware responsible for handling of customer software execution will include mission envelope protection logic, similar to one used in aircraft "fly-by-wire" systems, minimizing the risks of running potentially dangerous operational scenarios such as intentional or inadvertent draining the satellite batteries, pointing the sensitive imaging sensor at the Sun, or setting the satellite into a uncontrolled tumbling mode.
- The execution of the customer code will be vetted by the supervisor segment, that should be able to prevent any potentially dangerous command sequence and overtake control of the satellite, and in the extreme case to halt user software execution.
- Satellite command and control operators on the ground will be able to suspend or terminate the execution of the user mission software if any unforeseen problems will arise that are not resolved by automated safeguards.



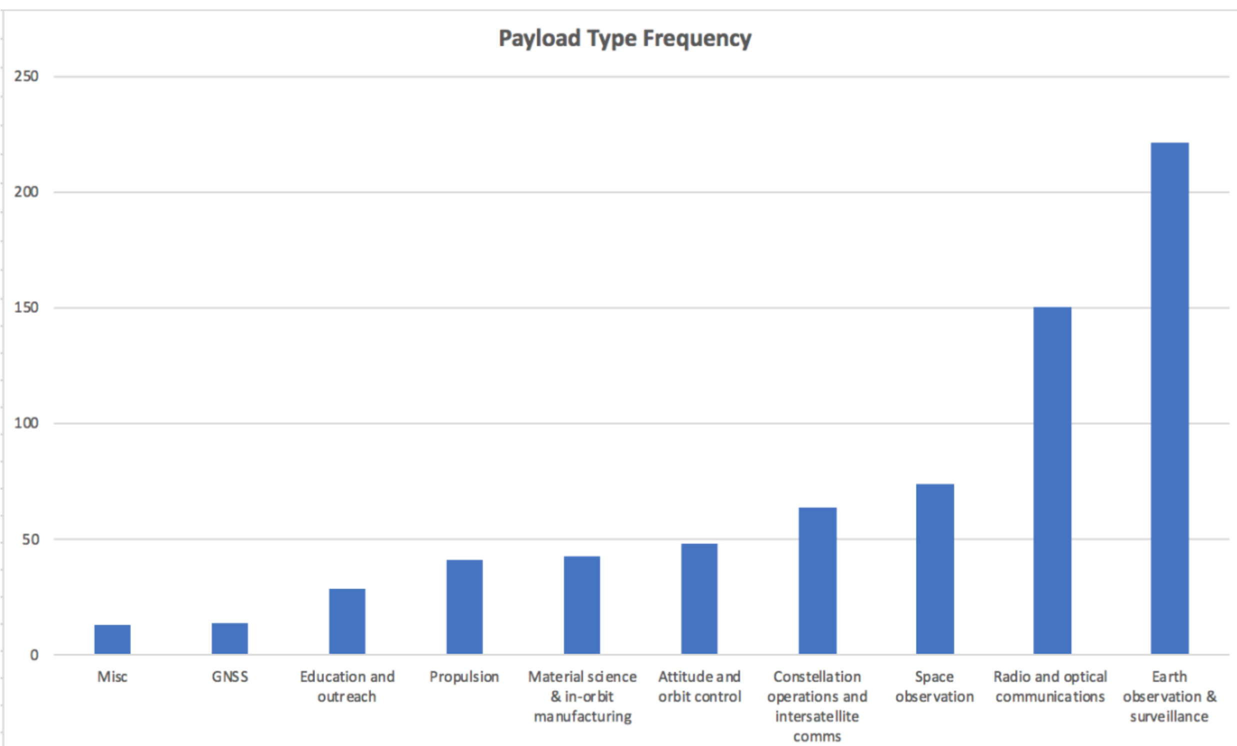
Top-level architecture of onboard-data handing and command subsystem

3. Commercial applications summary

Our first mission will aim to demonstrate the proof-of-concept viability, with early users expected to come from hobbyist communities and educational institutions. This mission will offer them the opportunity to participate in space exploration efforts at a level previously too difficult to achieve due to complexity, cost and regulation barriers of the space industry. Subsequent missions can host a more diverse array of instruments on much more robust platforms, satisfying the following requirements:

- Desired results can't be produced using ground-only platform.
- Implementation functionality depends mostly on software technology.
- Platform assets can be shared between customers on a single satellite (multi-tenancy)
- Product or service can offer cost advantages compared to currently available solutions

In all of the above cases this allows one satellite to host multiple tenants that can run access platform features in shared context, either sequentially or simultaneously. With the launch cost of even the smallest 1U cubesat around 100,000 USD and development timelines in a range of 1.5-2 years, availability of "pay-per-use" access to space-based platform can dramatically improve the cost-to-benefit ratio for development of any satellite-based technology. A review of the planned nanosatellite missions from 2019 to 2023 reveal that most common mission payloads are Earth observation instruments in various spectral bands and radio/optical communication equipment, that can allow both sharing of access between multiple customers and include considerable ratio of software-defined components, as illustrated in the chart below:



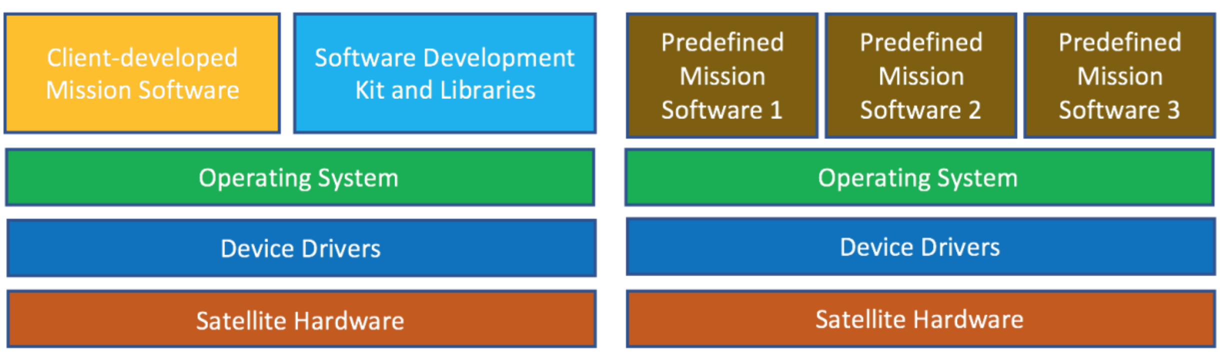
Summary of planned nanosatellite mission types (2019 – 2023)

4.1 Possible satellite service types

The implementation scenarios of the proposed shared-access satellite services can be broadly grouped into the following two areas:

- "***Satellite-as-a-service***" - this can be a first step beyond technology demonstrator mission. This solution will be similar to "IaaS" (infrastructure-as-a-service) or "PaaS" (platform-as-a-service) offerings from cloud computing vendors. The primary business purpose of this platform will be a development and qualification service with the possibility of hosting customer-developed applications subject to platform capabilities. Expected use cases will be testing of the new control algorithms, qualification of mission software to be used on other space missions or performing software experiments that would be too risky to trial on a larger and more costly satellite. This service will be initially aimed to the early adopters of our technology – small companies and individual entrepreneurs.
- "***Mission-as-a-service***" or **"*software-defined satellite*"** - this is an option possible when sufficient funding is available and sufficient experience gained, built on top of our previous technology, similar to the "SaaS" (software-as-a-service) solutions in the IT industry. With this level of service, more capable satellite hardware and software tools will become available, customized for the client's needs. A number of different missions can be executed on this type of satellite platform, depending on the available payload instruments and subsystem capabilities. A single satellite can also host multiple instruments with sufficient capabilities to allow customers to run their software packages in parallel.

The major difference between those service types is illustrated in the diagram below, being that in a "satellite-as-a-service" platform, the customers are responsible for the development of the entire suit of mission software, while for the "mission-as-a-service" platform they would already have multiple ready-to-use software packages to run and operate, depending on the selected mission type.



"Software-as-a-service" vs "mission-as-a-service" platform architecture

Both types of service can be scaled up to meet any level of customer demand, using either more robust hardware for subsequent satellite generations or increasing the number of satellites in the orbital constellation and ground stations to improve communication coverage.

The early implementation of these services may rely largely on nanosatellite hardware, but later generations of the same service can use larger and more diverse satellite platforms.

4.2 Application examples

Summarized below are the possible business application areas of our solution, using either "satellite-as-a-service" or "mission-as-a-service" platform:

- ***Science and education*** – give university students and researchers alike the ability to learn, develop and operate mission software for real spacecraft. Additionally, instead of going through the expense of building and launching their own full-scale earth observation, astronomy or space physics experiment into space, the research institution can use a shared-access satellite platform, similar in design to our initial technology demonstrator, but with more advanced capabilities in terms of instrument features and performance.
- ***Space software qualification*** – gives small and medium enterprises in space industry a chance to test and qualify their software products in the real space environment, without having to directly finance cost of building and launching their own satellites. This option can be also be offered for larger aerospace companies, such as Airbus Defence and Space to provide a quicker development cycle for their prototype technology projects. Examples of software elements that can validated using such a platform include:
    - Attitude and orbit determination and control algorithms
    - Sensor data processing and compression code
    - Error detection and correction algorithms for data storage and transmission
    - Software solutions for improving radiation-tolerance
    - Testing and development of various EM modulation and encoding schemes using provided software-defined radio or optical communications equipment
- ***Space app development*** – offers one of the most potentially valuable applications, allowing anyone to try their own ideas on our satellite platform. It might not be possible to predict all the useful outcomes of this area, but the net gains from opening up such an opportunity may be vast. Examples of such applications include:
    - <u>Maritime and airborne vessel and container tracking</u> – the required technologies are already in place (AIS and ADS-B), so the most convenient and least expensive service would use a shared ADS-B and AIS receiver that can supply data feed to multiple consumers.
    - <u>IoT and M2M</u> (machine to machine communications) – a low-bandwidth/high coverage communication space-based hardware can be shared between multiple software applications, each customized to the specific type of ground element of the system.
    - <u>Inter-satellite communications & cooperation</u> – a constellation of satellites can be used to provide test and development platforms for a wide array of possible software solutions. Inter-satellite communications and distributed-instrument satellite missions will need actual space hardware to fully qualify any software parts.

- ***Emerging technology demonstrators*** - a number of promising applications that can potentially revolutionize space the industry will need a thorough research and development phase before reaching required technology maturity level. Many of the technology elements are software defined and therefore would benefit from our proposed services. Examples given below:
  - Virtual reality – engage people by using the satellite cameras to provide an immersive experience of being in space. It is expected to be very software-intensive side in terms of implementation and will need an actual space environment to be fully immersive.
  - Space robotics - in-orbit satellite diagnostics, repair and manufacturing is another emerging field, with many corporate players interested in this area, but requires extensive development and testing of both hardware and software.
  - Asteroid mining – development of spacecraft able to perform asteroid rendezvous and assessment of extraterrestrial mineral resources has already begun. An opportunity to test different software solutions for multiple customers can be offered on a single satellite performing an asteroid flyby mission.
  - Quantum cryptography and secure communications in space – as it needs both an in-orbit element and depends on the proper software implementation, a space-based testing platform will be a valuable opportunity for interested parties.
  - Artificial intelligence for autonomous mission operations – in a similar manner, both in-orbit computing hardware and extensive software development efforts are required for this area of research, so this may become one of the most valuable applications for our service.
- ***Government programs*** – here, the best opportunity is offering the reduced cost of implementation due to the advantages of our on-demand, shared-access architecture. A more specific list of examples is given below:
  - Disaster monitoring – our platform can be rented out to national agencies, such as meteorological and emergency services to run their own missions instead of designing, testing, launching and operating their own satellites, provided our satellite is equipped with sufficiently capable instruments. During times of major disasters, the availability of the satellite service can be scaled up in response to demand.
  - Navigation services – with sufficiently large constellation, an *ad-hoc* global or regional navigation service system can be re-created if the primary GNSS, like GPS or Galileo becomes unavailable, using software-defined mission package and miniaturized, but sufficiently precise atomic clocks on the satellites.

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