Internet of Things Concept of Operations

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Contents

Table of Figures

Table of Tables

Revision History

Revision	Date	Comments
1.0	November 2020	Initial release

1 Introduction

The Open Source Satellite (OSSAT) is a micro-satellite project from KISPE Space (KISPE). This platform is designed to be a high value for money system, with a rapid turnaround to launch. The platform will support satellites between 25 to 250kg and is targeted to be versatile to allow it to be used for multiple applications without modification.

The design of the standard platform will be open source and available from the project's website within 12 months of the first launch.

In order to ensure that the OSSAT design is sufficiently flexible to meet the needs of multiple applications, KISPE are collating information on the Concept of Operations (CONOPs) for different applications, which will be used to derive the needs of the platform and help drive the platform solution.

1.1 Scope

This document provides a CONOPs for a generic Internet of Things (IoT) application for the Open Source Satellite. Since this is a generic CONOPs covering an IoT application, there may be aspects which vary from other specific IoT applications. If there is an IoT variant which sits outside of the CONOPs illustrated in this document, then a supplementary CONOPs may be generated.

This material has been derived from either publicly available information or from collaborators who have made material available to KISPE as part of the OSSAT Programme.

1.2 Applicable Documents

Applicable documents in the following text are identified by AD-n, where 'n; indicates the document as listed below:

AD-#	Title	Document No.	Date
1	Open Source Satellite Application Concept of Operations Template	KS-DOC-01107-01	03/08/2020

1.3 Reference Documents

Reference sources in the following text are identified by RD-n, where ‘n; indicates the source as listed below:

RD -#	Title	Document Location	Date
1	NewSpace Constellation Index	https://www.newspace.im/	27/07/20
2	On-orbit Performance of the ORBCOMM Spacecraft Constellation	B. T. Patel, et al. “On-Orbit Performance of the ORBCOMM Spacecraft Constellation,” *13th AIAA/USU Conference on Small Satellites*, 1999. Available at: https://digitalcommons.usu.edu/smallsat/1999/all1999/31/	25/07/20
3	Lacuna Space: About Us	https://lacuna.space/about/	02/11/20
4	Open Satellite LoRaWAN at scale: Thomas Telkamp – The Things Conference 2019	https://www.youtube.com/watch?v=vWkuqVJL1Sg	24/07/20
5	About Fleet Space	https://www.fleet.space/about	27/07/20
6	Kepler Communications Technology	https://www.keplercommunications.com	26/07/20
7	Iridium NEXT on the eoPortal Directory	https://directory.eoportal.org/web/eoportal/satellite-missions/i/iridium-next	10/08/20
8	Globalstar Second Generation Article	https://spaceflight101.com/spacecraft/globalstar-g2/#:~:text= Image%3A%20Thales%20Alenia%20Space.%20Globalstar%E2%80%99s%20second%20generation%20of,to%20the%20Iridium%20 and%20Orbcomm%20Satellite%20Communication%20systems.	10/08/20
9	Inmarsat – Our Satellites	https://www.inmarsat.com/about-us/our-technology/our-satellites/	10/08/20
10	NanoAvionics M6P CubeSat Platform	https://nanoavionics.com/nanosatellite-buses	10/08/20

1.4 Acronyms and Abbreviations

The following abbreviations are used throughout this document:

AOCS	Attitude and Orbit Control Sub-system
CONOPs	Concept of Operations
EOL	End-Of-Life
FDIR	Failure Detection Isolation and Recovery
GEO	Geostationary Earth Orbit
GPS	Global Positioning System
ISL	Inter-Satellite Link
IoT	Internet of Things
KISPE	KISPE Space
LEO	Low-Earth Orbit
LEOP	Launch and Early Orbit Phase
M2M	Machine-to-Machine
MEMs	Micro-Electrical-Mechanical System
MTM	Magnetometer
MTQ	Magnetorquer
OBC	On-board Computer
OBDH	On-board Data Handling
OSSAT	Open Source Satellite
PM	Power Management System
PPS	Pulse-Per-Second
RF	Radio-Frequency
RW	Reaction Wheel
Rx	Receiver
SS	Sun Sensor
TT&C	Telemetry, Tracking & Command
Tx	Transmitter
UHF	Ultra-High Frequency

2 Mission Objectives and Overview

Internet of Things (IoT) is the interconnection of computing devices, using the internet and machine-to-machine (M2M) techniques to enable them to send and receive data. There are many applications of IoT which all relate to the ability to share information between devices.

There are currently over 30 active/planned constellations that are aiming to provide IoT coverage by 2022 [1]. The vast majority of these organisations are employing CubeSats as the means of operating their payloads in space. This is due to the relatively low-cost of building a CubeSat-based constellation. The IoT payloads could however be flown on a small satellite platform and this is likely the future of the market as discussed in the Payload Description section below. The majority of the IoT space market is focusing on the application of enabling the fast transfer of small amounts of data from low-power devices in remote locations to main networks. Global coverage is therefore a key requirement of any IoT network provider, as is the latency of the transmission of data.

Although the IoT market primarily consists of organisations utilising CubeSats, there a few exceptions which use larger spacecraft to offer an IoT service.

- The Iridium-NEXT constellation is a group of 860 kg spacecraft in a low Earth orbit (LEO), Walker-star configuration [7].
- Globalstar are an organisation operating in a similar fashion to Iridium whereby they provide IoT for low-power devices from a constellation of 700 kg spacecraft in LEO [8].
- Inmarsat also provide IoT to service low power devices transmitting small packets of data. However, their constellation operates in geostationary Earth orbit (GEO) [9].

The organisations listed above utilise far larger spacecraft than normal IoT operators as their constellations provide services other than IoT. All three examples provide cellular connection for users on the ground and offer a range of higher frequency communication capabilities. For this reason, this document will focus on the payload and operations of the organisations using CubeSats as it is these organisations that are most likely to utilise the OSSAT platform for their operations in the future. Therefore, the operations of the current IoT CubeSat spacecraft will provide a better understanding of the requirements of such a mission.

Figure 3-1 provides a high-level diagram of the general architecture of an IoT mission.

The top level objectives/capabilities of a satellite servicing this application are as given in Table 2-1.

Capability	Performance	Note
Reference Orbit	Sun-synchronous, altitude ~ 500 – 600 km.	IoT providers are all planning on launching constellations [1]. These are most commonly in Walker-Star configurations.
Spacecraft Type	CubeSats, variable size but most often 3U and 6U.	See the Mission Objectives and Overview above for a description of the current IoT market.
Spacecraft Design Life	3 – 5 years.	
Spacecraft Agility	Payload only requires nadir point with no fast slewing necessary.	See Payload Description section below.
Pointing Accuracy	± 5° for nadir point [2].	Pointing accuracy of the Orbcomm spacecraft and expected requirement for CubeSat and small satellite operations [2].
Payload Field of View	Omni-directional antennas deployed [2] [3] [4]. See the Payload Description section below.	Future generations of IoT payloads may move to higher gain antennas or multiple receivers with multiple receivers on the spacecraft [4].
Onboard Data Storage Requirement	Low data rates. Satellites receive IoT signals consisting of small packets of data.	As an omni-directional antenna with a low gain is sufficient, both the payload data rates and downlink data rate will be low.
Data Products	IoT sensor data. Received messages are timestamped by payload.	Payload requires GPS pulse-per-second signal and positional information from GNSS [2] [8].
Safety and Security	IoT payload data encrypted.	
Communications	Most payloads receive IoT data using UHF omni-directional antenna [2] [3] [4]. Platform antenna required for data downlink. IoT constellations will employ inter-satellite links (ISLs) [3] [4].	See Mission Architecture section below. IoT constellations are most likely to employ radio-frequency (RF) ISLs due to the stringent attitude control requirements placed on the platform if an optical ISL were to be used.
Payload Thermal	No highly stringent requirements.	IoT payloads consist of receivers and sometimes transmitters. It is not expected that such units will have stringent thermal requirements.

Capability	Performance	Note
Payload Power	Low power. Expected to be < 10 W.	Current generation of IoT payloads are built for CubeSats with low power generation capabilities. IoT organisations utilising a small satellite such as the OSSAT may fly multiple payloads on a single mission. This would of course increase the power requirement.
Propulsion Requirements	No propulsion required for normal payload operations	As IoT organisations are aiming to launch constellations, propulsion may be required for initial orbit acquisition to achieve the desired phasing with the rest of the constellation.

Table 2-1 Top-level objectives/capabilities of a satellite conducting an IoT mission.

3 Mission Architecture

An IoT mission would involve hosting a payload onboard the OSSAT that would receive IoT data from devices on the ground and relay this information to ground stations, through the platform's antenna. The ground station then uploads the data to the respective IoT provider's network/cloud. These IoT devices on the ground would likely be simple, low-power sensors providing a range of data on whatever application they are used for.

IoT payloads operate in one of two main ways. The first is that the IoT devices on the ground first transmit their data to a local terrestrial gateway. This gateway then transmits all of the local IoT data to a satellite that is within range (e.g. organisations such as Orbcomm, Fleet Space, etc. operate in this manner [2] [5]). The second way is that the individual IoT devices themselves transmit their data directly to the satellite (e.g. Lacuna Space [4]). The advantages of this are clear as you no longer need a terrestrial gateway device in the mission architecture to relay the IoT data. The aim for removing the need for a terrestrial gateway is that large numbers of IoT devices in the satellite's field of view could transmit data simultaneously (Lacuna Space state that they can receive, decode and store the data from 1000 simultaneous transmissions [4]). This does however mean that the payload receiver on the spacecraft must be very sensitive to pick up the weak, long-range signals the IoT devices would transmit.

Almost all IoT providers are aiming to launch constellations to provide global coverage for IoT devices. For operations within a constellation, the spacecraft also have inter-satellite links (ISLs) to allow the IoT data to be relayed from the receiving spacecraft to one that is in view of a ground station. This obviously decreases the latency of the IoT data service. It is likely that RF ISLs will be employed as optical ISLs introduce stringent attitude control requirements to the system which are not required for operation of the payload itself.

Figure 3-1 shows a generic architecture for an IoT mission.

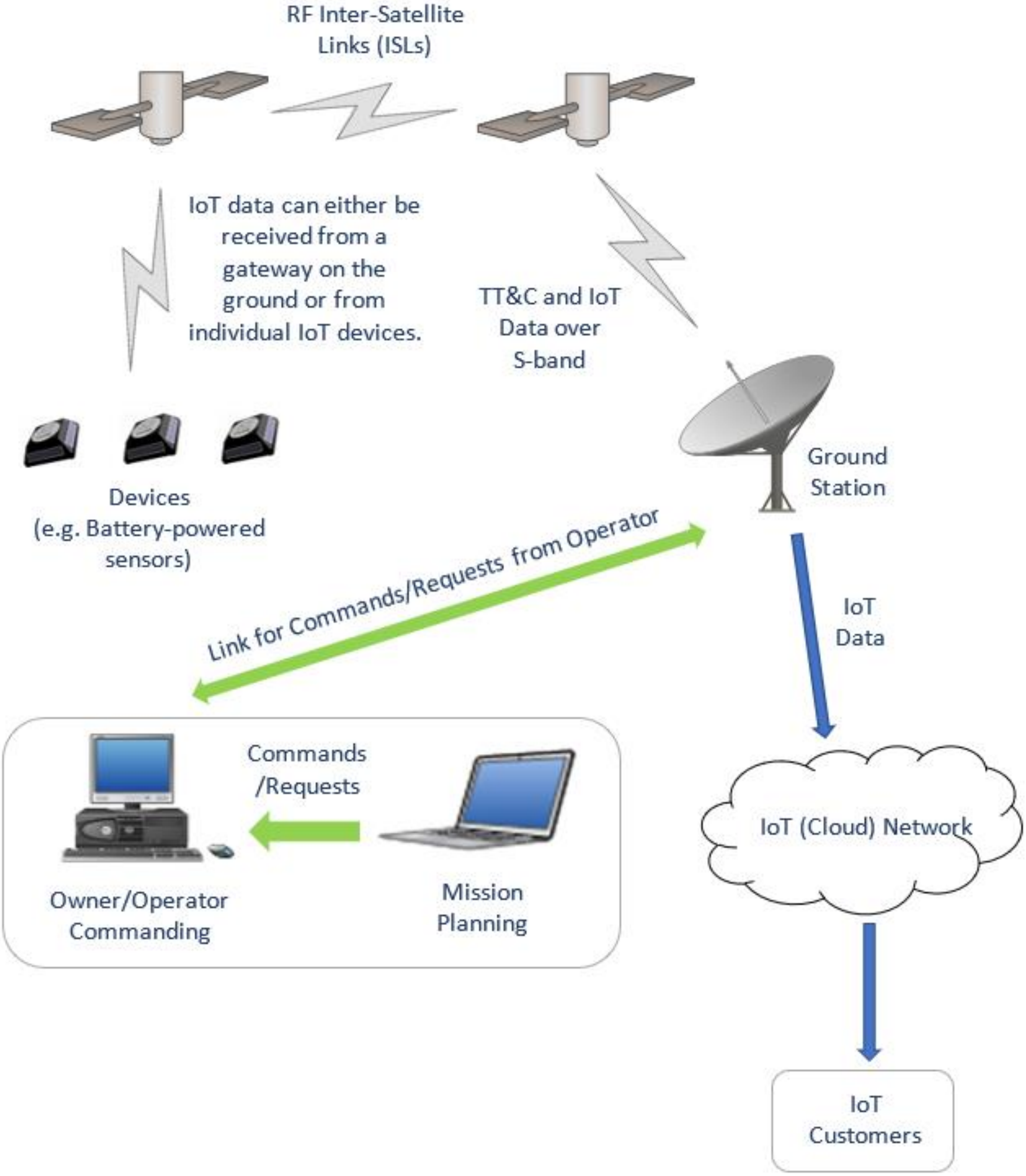

Figure 3-1 Generic Internet of Things Mission Architecture

4 Top level Payload Description

As stated in the introduction above, there are a large number of organisations aiming to provide global IoT coverage. Each of these is utilising their own payload to provide this service. Although the specifics of how this is achieved will vary from payload to payload, the top-level designs are broadly the same, with the main variations being described here.

IoT payloads generally consist of a receiver or transceiver (depending on whether the payload only receives signals or conducts the data downlink as well), receiving in the Ultra-High Frequency (UHF) band, between ~ 400 – 1000 MHz [4]. The payload receives data from devices on the ground and relays this to ground stations which in turn, upload this data to the relevant network. As with any kind of receiver and transmitter, the received signals will likely be passed through a low-noise amplifier (LNA) before undergoing filtering and digitalisation for storage. A pulse-per-second (PPS) signal provided by GNSS will be required to provide a synchronized source of time for the sampling of received signals [2]. This is necessary so that the IoT data can be decrypted upon reception on the ground as a standard source of time is available via the GNSS PPS.

Whether the platform antenna or the payload itself transmits the IoT data to the ground may vary between different organisations. Deployable, omni-directional antennas are most commonly used as the payload must be able to search for and receive IoT signals, sometimes from multiple devices, in a wide field of view. The IoT signals received are often circular polarized meaning helical antenna shapes are common [4] [5]. Most constellations are planning on using ISLs to allow transmission of the IoT data between spacecraft in the constellation to decrease the time it takes for data from devices to be transmitted to the main network.

Although the current versions of the IoT payloads onboard CubeSats have enabled the transmission of data from simple, low-power devices, as the complexity of the devices and the amount of data that users want to transmit increases in the future, it is reasonable to expect that the payloads will advance in their capabilities. If IoT organisations utilised larger spacecraft of a similar price to CubeSats (the OSSAT for example), then larger antennas or multiple payloads could be flown on a single mission. Flying multiple payloads on-board a single spacecraft would increase the capacity of the IoT service as a single satellite would be capable of detecting more signals at any moment in time. IoT payloads currently store their data on the platform computer but due to the small amount of data generated by such a payload, they would likely be able to store the data within the payload in the future. This would be inline with the OSSAT philosophy whereby there is a distinctive separation between the platform and the payload.

It is the payload types described above, or future generations of these payloads, that could be flown on-board the OSSAT in the future. As either the payloads' capabilities increase or more of the individual units are flown on a single mission, the IoT organisations would most likely require higher payload volume and a more capable satellite platform. It is for these specific applications that the OSSAT could provide the most sensible platform choice for a range of IoT providers. Of course, if the OSSAT could be offered as a solution at a similar price to that of a CubeSat, then the current payloads designed for CubeSats could well be flown on the OSSAT as well.

5 Satellite Architecture

Figure 5-1 shows a simplified, top-level block diagram of the satellite architecture required by the payload as detailed architectures of existing spacecraft are not readily available online. As the payload only requires a pointing accuracy of ± 5°, a simple sensor suite is sufficient. A combination of sun sensor (SS) and magnetometer (MTM) measurements would provide the necessary attitude determination accuracy for sufficient control over the spacecraft's attitude using reaction wheels (RWs). An additional gyroscope (GYRO) or inertial measurement unit (IMU) would also be required to continue to provide sufficient attitude determination accuracy during eclipse when the sun sensors would not be operational. Magnetorquers (MTQs) would also be included on-board to provide a means of conducting desaturation of the reaction wheels and potentially detumbling of the spacecraft after launch vehicle separation or when exiting a safe mode. Also included in Figure 5-1 is a GPS unit and radio frequency inter-satellite link (RF ISL).

This platform architecture is consistent with that of NanoAvionics M6P CubeSat platform which the IoT organisation Lacuna Space have previously utilised for their payload [4] [10]. The payload block diagram included below is a highly simplified version of an IoT payload. Depicted is also an additional payload mass memory unit which is inline with the OSSAT philosophy.

Additional acronyms used in Figure 5-1 include: attitude and orbit control system (AOCS), on-board computer (OBC), power management system (PM), transmitter (Tx), receiver (Rx) and transceiver (TRx).

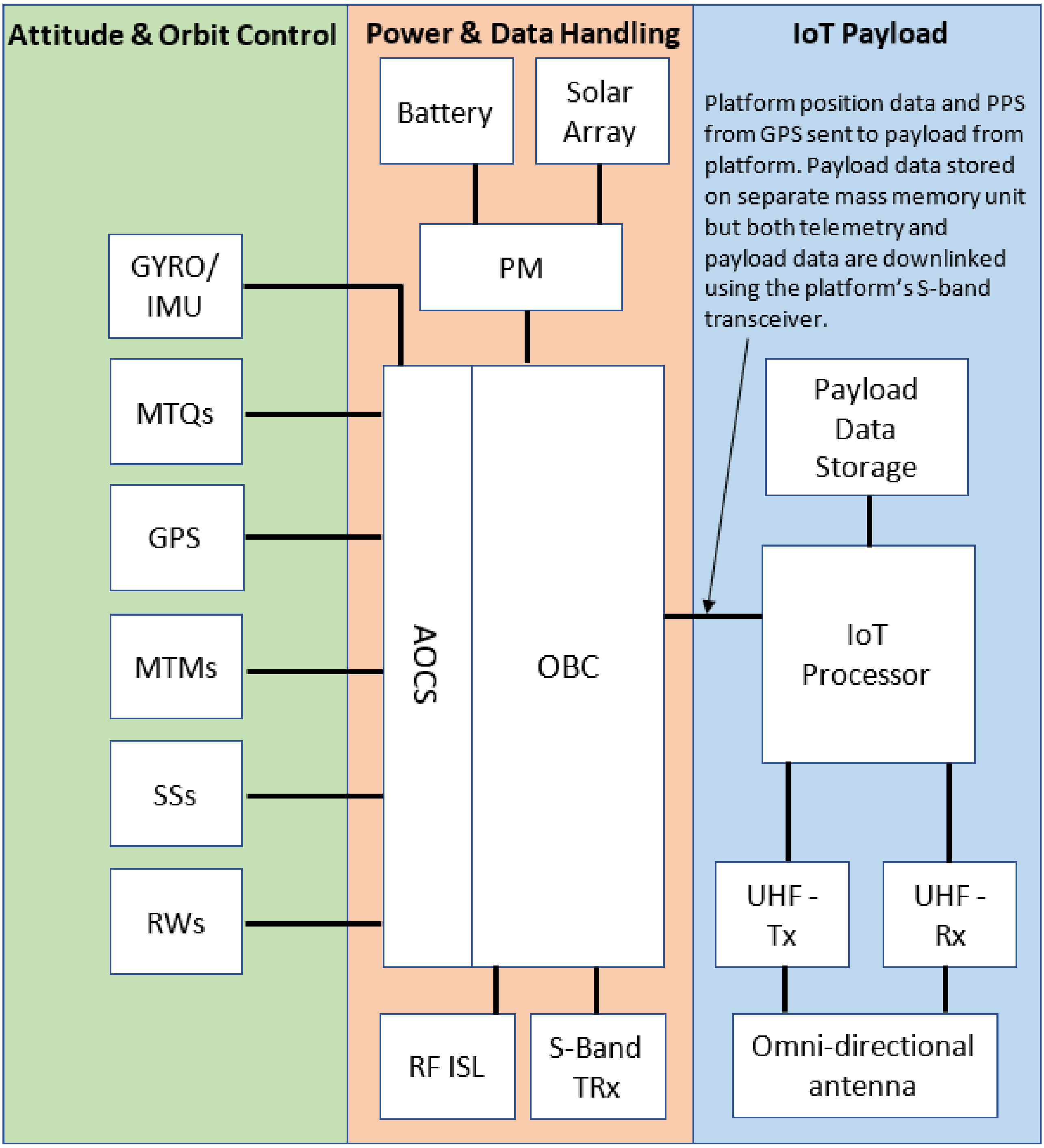

Figure 5-1 Top-level satellite architecture required by IoT payload.

6 Top level Platform/Mission Description

The platform/mission needs to provide the following functions:

6.1 Orbit

- The majority of constellations providing an IoT service have their spacecraft in LEO. Inmarsat are the exception to this rule with their spacecraft at GEO. As is described in the Mission Objectives & Aims section, they are however not a good example of the type of IoT mission that the OSSAT will service.
- The CubeSat IoT constellations (e.g. Lacuna Space, Fleet Space, Kepler, etc.) have their spacecraft in sun-synchronous orbits of around 500 - 600 km altitude [4] [5] [6]. This orbit choice is likely driven by both the availability of launch vehicles and the benefits of a sun-synchronous orbit which can provide global coverage due to the precession of such an orbit. The low altitude is also beneficial for the payload operation as the received power in the payload receiver would be higher, reducing the required sensitivity of the payload.
- One of the few IoT constellations employing small satellites, the Orbcomm constellation (~45 kg spacecraft), has its spacecraft in orbits with a 720 km altitude and 45° inclination (likely chosen to maximise coverage of moderate latitudes).
- The orbit required would be defined by the IoT payload provider whose constellation the OSSAT mission would most likely join.

6.2 Platform TT&C

- If the IoT payload consists of only a receiver it will receive data from the IoT devices and transmit this to ground stations using the platform transceiver. It is likely that the downlink of payload data will take place over S-band due to the high number of ground stations that can communicate at this frequency. Some IoT payloads may also include a transmitter and will therefore be capable of transmitting as well as receiving. This may mean that the payload itself can conduct the IoT data downlink which will remove the need to use the platform transceiver. This transmission would take place in the same UHF band that the payload receivers use currently.
- ISLs are included in most IoT constellation plans to transmit IoT data between spacecraft. This reduces the amount of time it takes for the IoT data to be transmitted to a ground station and subsequently onto the appropriate network or cloud. These will be RF ISLs as they will provide a sufficient data rate for the transfer of the low volumes of IoT data. The alternative optical ISLs also introduce an increased attitude control accuracy to the platform which is an unnecessary complication for this application.

6.3 OBDH

- Although some IoT organisations store their payload data on the platform, this will not be the case for implementation on the OSSAT. The OSSAT will have a clear delineation between the platform and the payload and will therefore require the payload to have its own mass memory module. This is unlikely to be a problem for this application as the data rates of the payload are low, resulting in a small amount of required memory storage. It would however require a change in the payloads as most payload providers will currently rely on the platform for data storage. Whether this additional payload data storage is provided by the payload provider or by the OSSAT programme will have to be determined.

- Unless the IoT payloads can conduct the downlink of their data, the platform antenna will have to be used. This will require the payload data to be routed through the on-board computer for downlink. Doing this does however reduce the platform/payload delineation and it would therefore be preferable that the payload can downlink the IoT data itself. The same is also true for use of ISLs which may also need be connected to the platform computer. If the ISLs are only required by the payload then the system could be configured such that the ISL is only connected to the payload. With the IoT data storage most likely existing within the payload, a command from the platform could then trigger the payload to send its data over the ISL without it having to be routed through the platform.

6.4 Attitude and Orbit control

- Only nadir pointing is required by IoT payloads as they all currently utilise omni-directional antennas. The pointing accuracy requirement is only ± 5° (the attitude control requirement of the Orbcomm satellites [2]). This means that only a relatively simple sensor and actuator suite is required to provide a sufficient level of attitude determination and control accuracy. This is described in detail in the Platform Architecture section above. An IMU or gyroscope unit will also be required to compensate for the loss of sun sensor measurements during eclipse.
- The IoT payloads will require GPS locational data which is used to both timestamp the received IoT messages and provide a PPS signal for the receiver. GPS data is also required by the payload so that it can conduct automatic frequency changes, depending on which parts of the world the satellite is currently over.
- As most IoT signals transmitting to space are circular polarized, the spacecraft's attitude about its nadir pointing axis has no affect on the reception of UHF signals [4]. This means that the spacecraft yaw does not need to be tightly controlled.

6.5 Power

- As an IoT payload must be available to detect IoT signals over any part of the world, on both land and sea, the payload will be on all of the time. It will however be able to be turned off by command from the ground. The power requirement of the current generation of IoT payloads is low, most likely < 10 W as these have been designed for operation on CubeSats with limited power generation capabilities.
- Future generations of IoT payloads may have a higher power requirements as they begin to utilise higher gain antennas or fly multiple receivers on the spacecraft (see the Payload Description section above for more information).

6.6 Thermal

- IoT payloads consist of a transmitter, receiver and payload processor. They are therefore not expected to have highly stringent thermal requirements.

6.7 Structure

- Deployable antennas are required for this application. The CubeSat payloads employed by organisations such as Lacuna Space and Fleet Space use omni-directional, deployable antennas as shown in Figure 6-1 [4] [5]. The payload will therefore require an external view for deployment of its antenna. The deployable mechanism will also need to be triggered by a command from the platform during the platform and payload commissioning.
- The IoT CubeSat payloads are small, e.g. Lacuna Space's current generation is only 1 kg and requires 1U of CubeSat space [4]. Future generations of IoT payloads may increase in size or more than one receiver may be flown on a single spacecraft which would in turn increase the payload volume required.
- It is likely that the payload will require an electromagnetically 'quiet' environment as the receiver must be sensitive enough to detect weak IoT signals, transmitted from the ground. This is going to especially be the case for organisations such as Lacuna Space who detect IoT signals transmitted directly from the individual sensor devices on the ground (see the Payload Description section for more information).

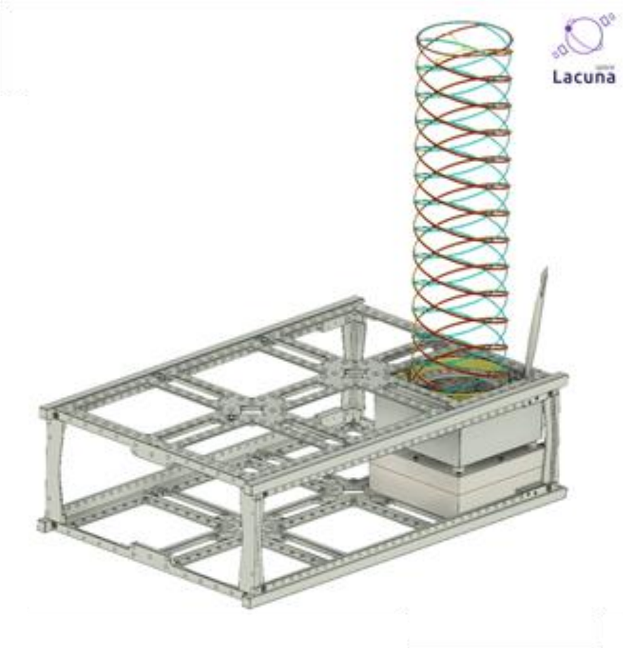

Figure 6-1 The deployable antenna used by Lacuna Space on the NanoAvionics M6P platform [4].

6.8 Propulsion

- The IoT application itself does not require any propulsion during nominal operations.
- However, as organisations aiming to provide a global IoT service are utilising constellations to do this, a propulsion system may be required to conduct this initial orbit acquisition. This may involve achieving the required phasing with the rest of the satellites in the same orbital plane.
- Recent changes in FCC regulations may also drive the need for including a propulsion system on-board the spacecraft. The FCC now provide a fast-tracked, cheaper licensing procedure if the spacecraft operator can guarantee that their platform will de-orbit in less than 6 years after the end of the mission. The OSSAT community must also keep up to date with similar regulation changes that may take place in the UK which might lead to the OSSAT having propulsive capabilities as standard.

7 Operations Overview

7.1 Pre-launch

- The platform will likely be powered off during launch to prevent the spacecraft from activating any powered functions on the payload prior to separation. There is also no need for the payload to be powered during launch and operating in this fashion simplifies discussions with launch agencies
- If the platform includes a propulsion system then fuelling activities will need to take place before attachment to the launch vehicle separation system.
- Functional testing will be carried out to ensure that the satellite is fit for flight. It will then either be attached to the launch vehicle separation system or loaded into a dispenser if the spacecraft is a CubeSat.

7.2 Launch and Early Orbit Phase

- On separation from the launcher the following activities will have to be undertaken by the platform with respect to the payload:
    - Platform commissioning will take place. This would typically occur during the first few link sessions with the spacecraft although autonomous platform commissioning may be implemented on the OSSAT. This would initially be the calibration of the sun sensors and magnetometers. This calibration may be able to be conducted during the initial tumbling of the vehicle. Subsequent calibration of gyroscopes and IMUs may commence either during or after detumbling.
    - The spacecraft will be detumbled and deploy any deployable structures. The spacecraft would most likely nadir point before deploying the payload antenna which will require a deployment signal/pulse.
    - If the platform includes a chemical, monopropellant propulsion system then de-poisoning of the catalytic beds will be required after separation. This procedure is required to burn off the atmospheric gases which would have been deposited on the catalytic beds during the launch.
    - Payload commissioning must take place. See section below.
- There are two possibilities for whether or not the spacecraft will have to transfer to an operational orbit:
    - Assuming that the desired orbit will be a near-polar LEO at ~ 500 km altitude (the case for the majority of IoT providers), the spacecraft could be placed in this orbit with no transfer required.
    - If the spacecraft is joining an existing IoT constellation and the platform has propulsive capabilities, then an orbital phasing manoeuvre may be required to reach an operational orbit. This can be achieved with a two-burn manoeuvre during which the spacecraft transfers to a phasing orbit until the desired phasing with the rest of the constellation has been achieved. At this point, a second burn is conducted to return the

semi-major axis and eccentricity to their initial values. The total duration of this orbit transfer will depend directly on the change in true anomaly required to place the spacecraft in the required position in the constellation.

7.3 Payload commissioning

- Before payload commissioning can commence, the satellite must be in the following state:
    - The spacecraft will have to be nadir pointing to allow the payload antenna to receive test signals from the ground. This would be required for all generations of an IoT payload (see the Payload Description section).
- The satellite platform must do the following to allow the payload commissioning to take place:
    - The payload antenna must be deployed.
    - The platform will also need to provide a PPS signal from the GPS unit so that the payload receiver can operate. It is likely that the IoT operator will also want to check the payload's ability to automatically conduct frequency changes depending on what continent the spacecraft is currently over. This would require the platform to provide positional information from the GPS unit during payload commissioning, if the payload is capable of this type of operation.
- Activities involved with turning on payload for the first time:
    - Platform will likely retrieve diagnostic information from the payload and send the appropriate command for deployment of the antenna.
    - The IoT operator will want to confirm the downlink of data from payload to a ground station. They will also need to conduct payload health checks and downlink the diagnostics information to the ground.

7.4 Nominal operations

- Payload On/Off Times:
    - The payload will always be turned on due to its low power requirement and the need to provide global IoT coverage. It will however be possible to turn the payload off by command as this will likely be necessary if the platform were to enter a safe mode upon detection of a fault.
- The payload command process and format:
    - The command process and format will vary between different IoT payload providers. Commands for the payload will however be sent with the commands for the platform via the platform S-band antenna. The platform will then send the appropriate commands to the payload.
- The different modes of the IoT payload:
    - The IoT payload will be on all of the time to detect and receive data from the IoT devices/gateways on the ground.

  - Some IoT payloads may also have a mode which allows the receiver to scan across multiple frequencies to determine and account for the noise environment.
  - Additional modes may be present on different IoT payloads.
- Payload On/Off procedure:
  - The payload on/off procedure will vary for the different IoT payload providers. However, It will have to be ensured that before turning the payload off, the latest IoT data has been successfully stored on the payload mass memory unit. In case of an emergency which requires the payload to be turned off, it will have to be checked with the payload provider that it is acceptable to lose a small amount of IoT data.
- During payload operation, the following platform units will need to be activated:
  - The GPS unit will be required. See Platform Description.
  - Due to the low level of attitude control accuracy required and the fact that the payload will be on all of the time, no additional AOCS units will need to be activated during payload operations. However, the gyroscope or IMU may be able to be turned off during the sunlit part of the orbit and activated during eclipse.
- Payload pointing:
  - Only nadir pointing is required by the current generation of payloads.
  - For some IoT payloads, the platform transceiver may be used to downlink the payload data. Depending on where on the platform the S-band transceiver is located with respect to the payload antenna, the platform may need to slew to point the platform antenna at nadir. The platform may need to point and slew to track a ground station during telemetry and payload data downlink but this will depend on the required data rate to downlink all of the IoT data in a single link session.
  - There are no attitudes that must not occur in terms of damaging the payload. If the payload antenna is not pointed nadir however, the IoT service will not be being provided. The spacecraft can even be rotated about its nadir-pointing axis and still receive the UHF IoT data due to the use of circular polarized signals.
  - Low pointing accuracy requirement of ± 5° [2]. See Platform Description.
- Inter-Satellite Communications:
  - Most IoT organisations are planning on using ISLs to reduce the latency of their service. These are likely to be radio frequency inter-satellite links. See the Platform Description section for more information.
- Orbital Manoeuvres:
  - The payload will not require the spacecraft to conduct orbital manoeuvres during the nominal operations of the mission.
- Payload Deployables:
  - IoT payloads have deployable, omni-directional antennas.
  - Future generations of IoT payloads may have larger antennas or multiple payloads could be flown on the same spacecraft to increase the IoT

capability of a single spacecraft. This may require more than one antenna to be deployed on one spacecraft to accommodate a wider range of frequencies.

- Payload Time Requirements:
  - A PPS signal is required from the GPS unit by the receiver. This acts as the source of time synchronization for the sampling of the received IoT signals. See the Payload Description for more information.
  - The received IoT messages will also be timestamped by the payload using time from the GPS. See Platform Description.
- Payload Attitude/orbit data:
  - The payload will also likely require position data from the platform for automatic frequency changes over different countries.

7.5 ICD Questions

- Payload Mass/Volume:
  - The companies aiming to provide an IoT service using CubeSats employ very small payloads. E.g. the current Lacuna Space payload has a volume of 1U of CubeSat space [4].
  - Mass/volume will increase if IoT providers move towards higher-gain antennas or more payloads are flown on the same spacecraft to increase the IoT capability of a single platform.
- Payload position on platform:
  - The payload will require an external view as it has a deployable antenna.
  - The payload will likely require an electromagnetically 'quiet' environment. This is especially the case for payloads that detect IoT signals directly from the devices themselves as they need to be very sensitive to do this. This requirement will drive the payload's position on the platform with respect to platform electronics and other units generating magnetic fields.
- Payload Temperature Requirements:
  - The payload will likely not have stringent temperature requirements. See the Platform Description for more information.
- Payload power, data storage and downlink requirements:
  - The power requirements of the current generation of payloads are low. It is expected that they will require < 10 W of power during operation.
  - This may increase as the payload's capabilities advance in the future or more payloads are flown on one platform. See the Platform Description.
  - The data storage requirements are low as the payloads receive IoT messages with small amounts of data in them. Currently, IoT payloads store their data on the platform data storage. As the amount of data is low, it may be possible to have the IoT payloads store their data within the payload in the future which will be inline with the plan for the OSSAT.

7.6 Non-routine Operations

Non-routine operations are activities that do not happen on a regular basis. These activities will require operator interaction.

Examples of non-routine operations are:

- Uploading new software
    - Software updates will be likely for most types of IoT payloads [4].
- Critical commanding
- Collision avoidance
    - If the spacecraft has propulsive capabilities, it will be able to perform collision avoidance manoeuvres if the operator is notified of a conjunction with another object. Any collision avoidance manoeuvres would mean a loss of service for the payload for a period of time, reducing the constellation's coverage.
- End-of-mission activities
    - End-of-life activities are considered non-routine operations. See the End-of-Life section below for more information.
- For an IoT application, deployment of an antenna will be required. This may mean that the payload's power requirement increases briefly during the deployment period.

7.7 Non-nominal operations

In the event of an anomaly on-board, the satellite will place itself into a safe mode. This will either be a passive or an active safe mode, depending on the mission analysis results and the customer needs. When the platform enters safe mode, the payload will be switched off.

A passive safe mode results in the satellite entering a tumble state, with minimal units powered to conserve energy. Recovery from this state is driven manually, as investigations into the cause of the safe mode need to be conducted before the satellite is placed back into nominal operations.

Once the investigation has been concluded, the de-tumble and operational attitude recovery can follow the same approach as in the launch and early orbit phase (LEOP).

An active safe mode will place the satellite into a controlled thermally and power safe attitude, which is normally a spin around a single axis (i.e. a Thompson mode) or sun-pointing.

With respect to either a random or controlled spin, there are no known unacceptable attitudes for an IoT payload that should be considered during the design of the safe mode. It will have to be check with the payload provider that, during an emergency, the payload can be abruptly switched off and that a small amount of IoT data may be lost in the process.

8 Failure Detection Isolation and Recovery (FDIR)

At this stage it is proposed that the on-board platform FDIR for OSSAT will have the following typical functionality:

- Limit checking – *nominally current draw/temperature*
- Watchdogs – *handshaking with a unit to ensure that it is still operating correctly*
- Power switch trips/timeouts – *this will be for all switches including payload ones*
- UnderVoltage: Load shedding – *this will switch off the payload*
- Detection of Platform Bus failure/blockages
- AOCS error management

Apart from the on-board platform FDIR techniques described above, it is not expected that any additional FDIR will need to be provided by the platform for the payload.

9 End-of-life operations

- If a propulsion system is included on-board the OSSAT, then a de-orbit manoeuvre would likely be performed at the end of life. This would involve reducing the perigee of the spacecraft's orbit to increase the atmospheric drag that the platform is subjected to. Inclusion of such a manoeuvre into the OSSAT CONOPs would need to be taken into account when deriving the propellant mass budget of the spacecraft as enough fuel would be required at the EOL to perform this orbit transfer. During the EOL operations, after the de-orbit manoeuvre has been conducted, the platform would need to burn its remaining propellant to reduce the chance of any on-orbit explosions or fragmentations occurring.
- As the payload for this application consists of a receiver and transmitter it will need to be ensured that these units will not continue to transmit at the EOL of the mission and will not turn back on at any point in the future.

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