Synthetic Aperture Radar

Concept of Operations

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Revision History

Revision	Date	Comments
1.0	July 2021	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 and 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 Synthetic Aperture Radar (SAR) application for the Open Source Satellite. Since this is a generic CONOPs covering a SAR application, there may be aspects which vary from other specific SAR applications. If there is a SAR 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	E. Chuvieco’s, “*Fundamentals of satellite remote sensing: An Environmental Approach.”*	N/A	20/08/2020
2	Tippawan Wanwiwake, “A Microsatellite Based Synthetic Aperture radar (SAR).”	A Microsatellite Based Synthetic Aperture Radar (SAR). - Surrey Research Insight Open Access	20/08/2020
3	ICEYE SAR Product Guide	ICEYE-SAR-Product-Guide.pdf	20/08/2020
4	EOS SAR Website	https://eossar.com/sar-payload.html	20/08/2020
5	SSTL CARBSAR Datasheet	https://www.sstl.co.uk/getmedia/9841ec69-9114-49b0-9875-151f7292ea93/SSTL-CARBSAR.pdf	24/08/2020
6	A Tutorial on Synthetic Aperture Radar	https://core.ac.uk/download/pdf/31005519.pdf	24/08/2020
7	Capella Space Website	https://www.capellaspace.com/technology/	24/08/2020
8	ICEYE-X1 eoPortal Directory	https://directory.eoportal.org/web/eoportal/satellite-missions/i/iceye-x1	24/08/2020
9	York Space System’s S-Class Platform datasheet	https://www.yorkspacesystems.com/s-class/	24/08/2020
10	Satsearch.co	https://satsearch.co/	27/08/2020
11	FCC Streamline Smallsat Licensing Regulations Published (Article on Space News)	https://spacenews.com/fcc-streamlined-smallsat-licensing-regulations-published/?utm_source=dlvr.it&utm_medium=linkedin	27/08/2020
12	B. Pyne, et al. “Development and Performance Evaluation of Small SAR System for 100-kg Class Satellite.” *IEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 13, 2020.	Development and Performance Evaluation of Small SAR System for 100-kg Class Satellite - IEEE Journals & Magazine	05/11/2020
13	Capella-X-SAR eoPortal Webpage.	https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/capella-x-sar	05/11/2020

RD-#	Title	Document Location	Date
14	H. Saito, "Compact X-band synthetic aperture radar with deployable plane antenna and RF feeding system through non-contact waveguides." *Small Satellite Conference Proceedings*, vol. 2, 2016.	DigitalCommons@USU - Small Satellite Conference: Compact X-band Synthetic Aperture Radar with Deployable Plane Antenna and RF Feeding System through Non-contact Waveguides - Project of a 100kg-class SAR Satellite	05/11/2020

1.4 Acronyms and Abbreviations

The following abbreviations are used throughout this document:

AOCS	Attitude and Orbit Control Sub-system
CONOPs	Concept of Operations
EO	Earth Observation
EOL	End-Of-Life
FDIR	Failure Detection Isolation and Recovery
GPS	Global Positioning System
HV	Horizontal-Vertical
IADC	Inter-Agency Debris Coordination Committee
ISL	Inter-Satellite Link
KISPE	KISPE Space
LEO	Low-Earth Orbit
LEOP	Launch and Early Orbit Phase
MTM	Magnetometer
MTQ	Magnetorquer
OBC	On-board Computer
OBDH	On-board Data Handling
OSSAT	Open Source Satellite
PM	Power Management System
RW	Reaction Wheel
Rx	Receiver
SAR	Synthetic Aperture Radar
SS	Sun Sensor
TT&C	Telemetry, Tracking & Command
Tx	Transmitter
VV	Vertical-Vertical

2 Mission Objectives and Overview

Space-based Synthetic Aperture Radar (SAR) is a remote sensing technique which is capable of providing 2-dimensional or 3-dimensional reconstructed images of target areas on the ground and has wide applications for remote sensing and mapping of the Earth's surfaces. SAR is an active observation technique whereby a large antenna on a satellite simultaneously emits and receives microwaves. As the transmitted microwaves reflect off of the ground, the received echoes provide amplitude and phase data which can be used to reconstruct images. As SAR operates using microwaves, it can conduct imaging both during the day and night and is capable of penetrating cloud cover and adverse weather conditions which would make traditional Earth Observation (EO) techniques less effective [1].

The achievable resolution of imaging targets on the ground is directly proportional to the area of the antenna. Therefore, SAR missions have most commonly been conducted using larger spacecraft, such as the Canadian Space Agency's 2300 kg RADARSAT-2. These platforms allow a larger antenna to be deployed than on a small satellite [1]. However, as small satellite platforms provide a massive reduction in development costs, the number of SAR missions using spacecraft of ~ 100 - 200 kg mass have been increasing over the last few years [2]. Furthermore, the use of small satellites provides a more financially feasible method of building large constellations which can achieve fast global coverage and revisit imaging locations within a few hours [2].

Organisations such as ICEYE and Capella Space have small satellite SAR missions currently in operation and provide a timely imaging service to their customers [3]. They use satellite platforms of 85 kg and < 100 kg respectively to deploy large antenna structures, operating in the X-band. ICEYE and Capella Space are capable of image resolutions of 0.5 m, when operating in *Spotlight* mode [3, p. 21] [7]. Independent SAR payloads for small satellites are also currently being developed. EOS SAR offer a 50 kg payload, deploying a 2 - 7 m diameter antenna capable of achieving 1 m resolution on the ground [4]. Surrey Satellite Technology Limited (SSTL) and Oxford Space Systems are also in collaboration to produce a SAR payload for SSTL's 140 kg CARBSAR spacecraft [5].

Whereas in the past, synthetic aperture radar imaging was conducted on large spacecraft, recent developments in technology and the small satellite market make SAR a potential application of the Open Source Satellite. The OSSAT's mass range of 25 - 250 kg would be capable of accommodating such a payload, operating as an independent mission or as part of one of the SAR constellations that are in development. CubeSats are generally not used for SAR missions due to the large deployable antenna and high payload mass that is required. The OSSAT, with a low price point compared to the rest of the market, could provide a competitive alternative to other small satellite platforms for organisations building SAR constellations.

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

Capability	Performance	Note
Reference Orbit	~ 500 – 600 km, Sun-synchronous orbit with a repeating ground track [3] [4] [5].	The orbit used by ICEYE, Capella Space, NovaSAR and other, larger SAR missions.
Spacecraft Type	~ 100 – 200 kg for small satellite SAR missions.	See Platform Description for range of SAR spacecraft masses.
Spacecraft Design Life	5+ years [3] [5]	Lifetimes based on ICEYE's spacecraft and SSTL's CARBSAR.
Spacecraft Agility	Platform may be required to slew to conduct payload data downlink over an X-band transmitter.	The spacecraft will not need to slew during nominal operations of the payload.
Pointing Accuracy	Accurate attitude control required, < 0.1° pointing accuracy [9]. Highly stable platform required. ICEYE's platform provides a stability of 0.25 arcsec/s [9].	Required to provide a stable platform for the electronic beam steering during imaging [2] [3].
Payload Field of View	A large deployable antenna is required by the payload and must be nadir pointed.	May be a rectangular or parabolic antenna, ranging from ~ 3.5 – 7 m diameter. See the Payload Description section for more information.
Onboard Data Storage Requirement	Large data storage requirement. ~ 1-10 GB/imaging event [5].	SSTL's CARBSAR: 140 GB throughput/day for 45 images [5]. ICEYE spacecraft can only image for 180 s/orbit due to data storage limitations [8].
Data Products	SAR raw data. Includes amplitude and phase information of received, sampled signals.	Requires post-processing on the ground to generate the images.
Safety and Security	Unknown	
Communications	X-band transceiver required for payload data downlink.	SSTL's CARBSAR: 500 Mbps downlink, ICEYE: + 100 Mbps [3] [5].
Payload Thermal	Due to the inefficiency of RF payloads, the platform will need to remove a lot of heat from the payload.	See the Platform Description for more information.
Payload Power	Very high. ~ 1000 W peak power during imaging [14, p. 14].	See Platform Description for more information.
Propulsion Requirements	Not required for nominal operations of SAR mission.	Included on some SAR spacecraft to conduct de-orbiting at end-of-life [3] [9].

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

3 Mission Architecture

A synthetic aperture radar variant of the Open Source Satellite could be used as the platform for an organisation building a SAR constellation. The SAR constellations currently in development do not employ inter-satellite links (ISLs). This is primarily due to the large amount of data that SAR satellites generate.

SAR missions typically employ S-band and X-band transceivers for telemetry, command and control (TT&C) and payload data downlink, respectively [3]. Communication with the spacecraft can therefore take place at a range of ground stations around the world. A user will request imaging of a particular location/locations on the Earth and then mission analysis is conducted to calculate when a satellite in the constellation will next pass over that target. A scenario for the acquisition of the images is then presented to the customer for approval as the quality of images produced will depend on a number of parameters such as: the time of imaging, coverage of the area and the cross-track electronic beam steering required to image the target.

Upon approval from the customer, a schedule file of the imaging events to take place can be sent to the appropriate spacecraft during its next ground station contact. The spacecraft can then conduct the SAR imaging of the desired location and downlink the payload data over the X-band at the next ground station contact. The SAR data is then decoded and processed to generate the images the user requires. The images are quality controlled to ensure that they meet the requirements of the customer before they are finally made available to them [3, p. 29].

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

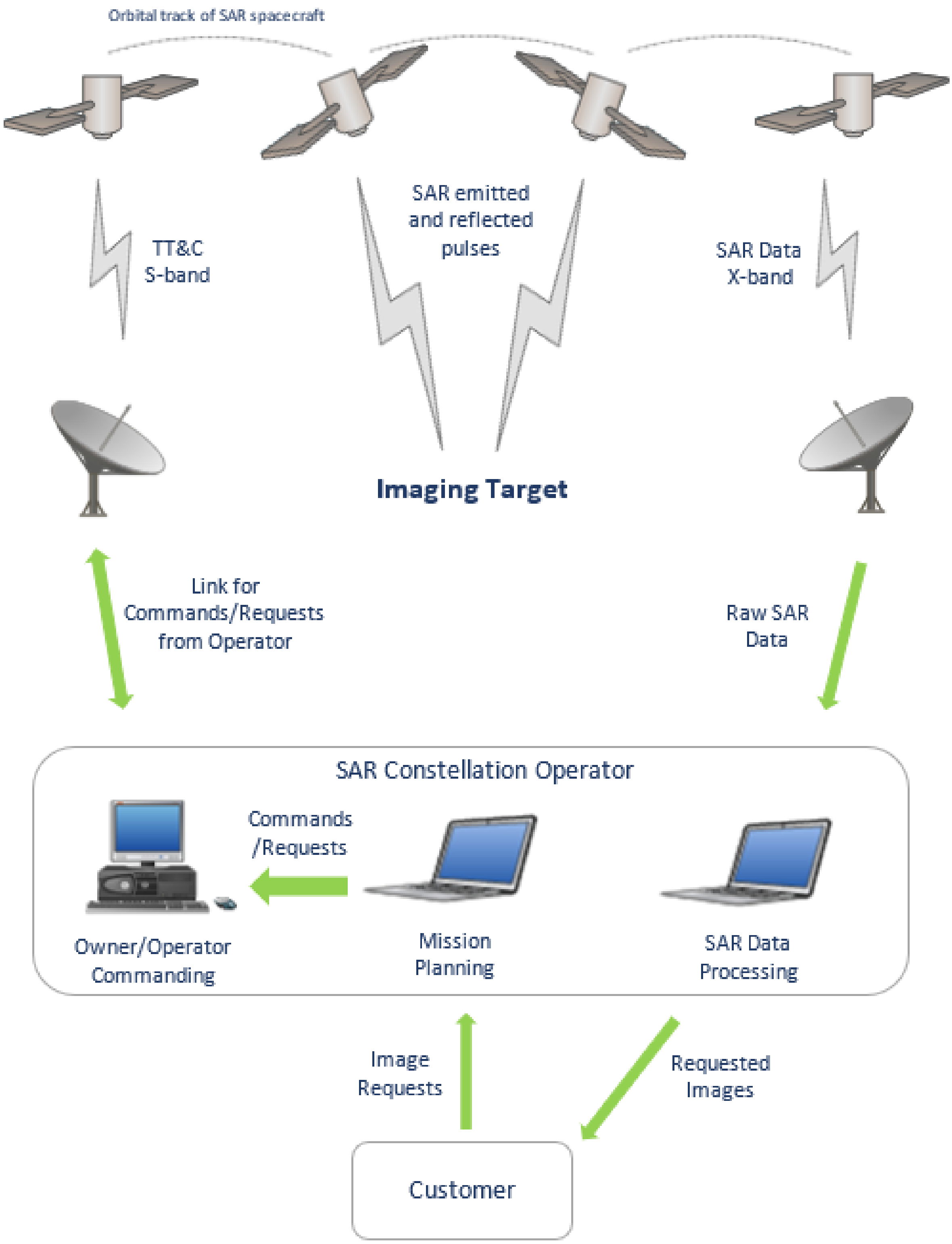

Figure 3-1 Generic SAR Mission Architecture

4 Top level Payload Description

SAR works by emitting microwaves at the ground and then detecting the reflections of these waves at some position along the spacecraft's orbital track. SAR has been conducted by spacecraft using a range of frequencies in the microwave part of the radio spectrum. Spacecraft such as ERS-1, Radarsat and Envisat utilised C-band SAR whereas the majority of recent small satellite spacecraft operate in the X-band frequency range [1]. Increasing the frequency of the emitted microwaves enables images of a higher resolution to be generated, as shown by Equation 1 [1, p. 68]:

$$R_s = \frac{\lambda\, h}{L} \tag{1}$$

Where: R_s is the minimum size of objects on the ground which can be detected in either the along-track or cross-track direction, h is the spacecraft's altitude, λ is the observational wavelength and L is the length of the antenna in the direction that the resolution is being calculated for.

High mass spacecraft such as Envisat and Radarsat are capable of deploying very large antennas, decreasing the minimum size of detectable objects as shown by Equation 1. Smaller spacecraft, such as those operated by ICEYE and Capella Space make up for their loss of resolution due to smaller antenna apertures by observing at a higher frequency. ICEYE spacecraft have an antenna of size 3.2 x 0.4 m [3, p.7]. The EOS SAR payload is offered with a circular antenna of diameter 2 – 7 m [4]. As Equation 1 indicates, the larger the distance between the antenna and the target (in the case of spacecraft the altitude), the lower the achievable resolution. SAR makes use of the synthetic aperture technique whereby emitting and receiving the microwaves at different physical locations in its orbit generates a *virtual* telescope with a diameter equal to the distance between the locations of emittance and reception of the microwaves. Utilising this technique compensates for the loss of resolution from observing the target from the high altitudes of spacecraft [1].

Observation can take place in a range of modes which are further described in the Nominal Operations section below. These different modes compensate for the trade-off between image resolution and the spatial area covered in a single observation, which is inherent to SAR. When observing, microwaves are continually emitted from the antenna in the form of consecutive, long-duration pulses which sweep up or down in frequency across the whole bandwidth of observation. Increasing the bandwidth across which observations are made reduces the impact of noise in the received signals and compensates for the use of higher observation frequencies (which increases the noise in the receiver) [3, p. 10]. Increasing the bandwidth does however increase the data storage requirements.

A SAR payload is capable of simultaneous transmission and reception of microwaves. Upon detection, amplitude and phase information of the received signals is stored, along with the time of detection which is required for the post-processing of the raw SAR data. The received signals are passed through a low noise amplifier (LNA), having been down-converted from a higher frequency depending on the maximum input frequency of the LNA. Having then been filtered, the analogue signals are digitised for storage [2]. Figure 4-1 shows a SAR payload block diagram. A GPS pulse-per-second (PPS) signal may be required to act as the source of time synchronization between the payload's transmitter and receiver. A crystal oscillator may however be sufficient for this purpose [2, p. 5].

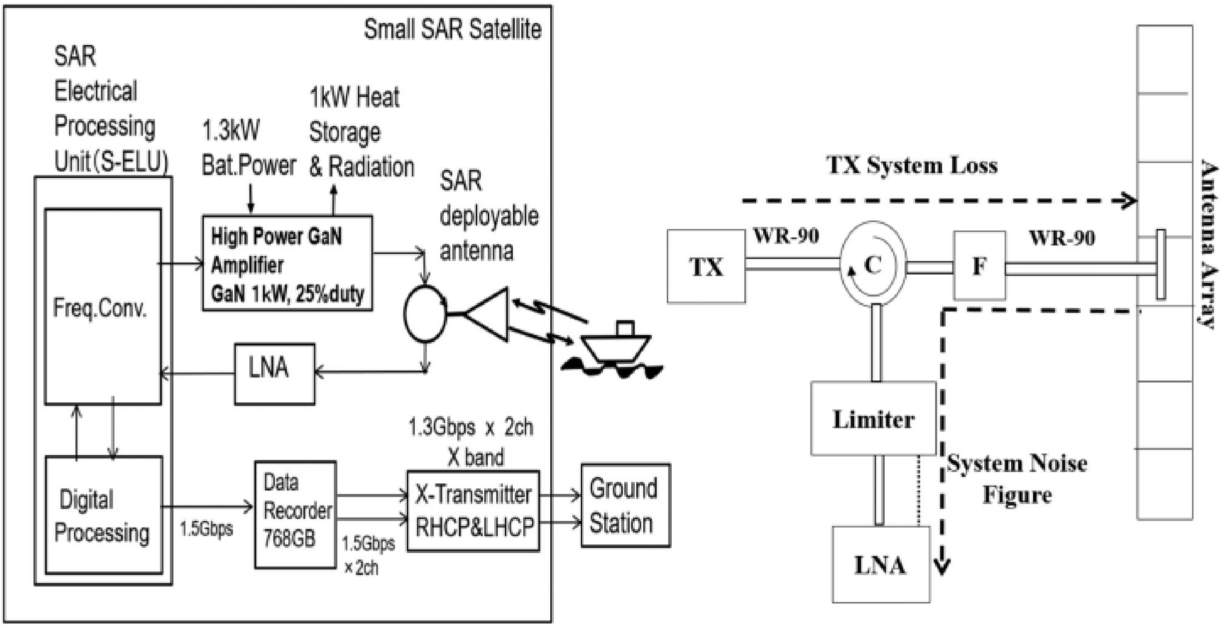

Figure 4-1 Generic small satellite SAR system diagram [12]

Some additional features of synthetic aperture radar are often included in a mission:

- Polarimetry: Receiving signals in a range of polarities can allow the detection of a wider range of objects on the ground, in greater detail, as different surfaces reflect microwaves in different polarisations [2, p. 41]. Small satellites such as those of ICEYE only receive in a single polarisation (vertical-vertical (VV)) [3]. This is likely driven by the size of the platform and the payload mass permissible on-board. The EOS SAR payload can observe in both VV and HV (horizontal-vertical) polarisations [4].
- Interferometry: An interferometric mode is sometimes utilised with constellations of SAR spacecraft and can achieve extremely high levels of resolution. Interferometry involves observation of the same location from different positions, at the same time (i.e. from different spacecraft in a constellation). The difference in the measured phases from both positions can then be compared which gives detailed range information, from which an image can be generated [6, p. 19]. SAR interferometry has applications in: accurate surface topography, detection of moving objects, measurement of sea ice drift and glacier flow and the study of seismic deformations, to name a few [6, p. 19]. The main benefit of SAR interferometry is the ability to observe the dynamic behaviour of targets, being able to record changes with respect to time.

5 Satellite Architecture

Figure 5-1 shows a top-level diagram of the satellite architecture required for a SAR mission. This figure provides an overview of the types of equipment that a SAR spacecraft would typically require as detailed architectures of existing spacecraft are not readily available online.

As described in more detail in the Platform Description section below, SAR missions require a highly stable platform for their *Spotlight* mode where the deployed antenna electronically points its beam at a particular location. AOCS components such as inertial measurement units (IMUs)/gyroscopes (GYRO), star trackers (ST) and reaction wheels (RW) are therefore required to achieve a < 0.1° pointing accuracy and ~ 0.25 arcsec/s stability [9]. Magnetorquers (MTQs) would also be included on-board to provide a means of conducting desaturation of the reaction wheels and detumbling of the spacecraft after launch vehicle separation or when exiting a safe mode. A separate payload data storage is also included. This is in line with the current plan for the OSSAT where payload data will not be stored in the main platform data storage.

The block diagram representing the SAR payload is based on the generic design presented in Figure 4-1, with the following acronyms used: low noise amplifier (LNA) and high power amplifier (HPA).

The following additional acronyms are also used in Figure 5-1: attitude and orbit control system (AOCS), on-board computer (OBC), power management system (PM), transmitter (Tx), receiver (Rx), transceiver (TRx), sun sensor (SS) and magnetometer (MTM).

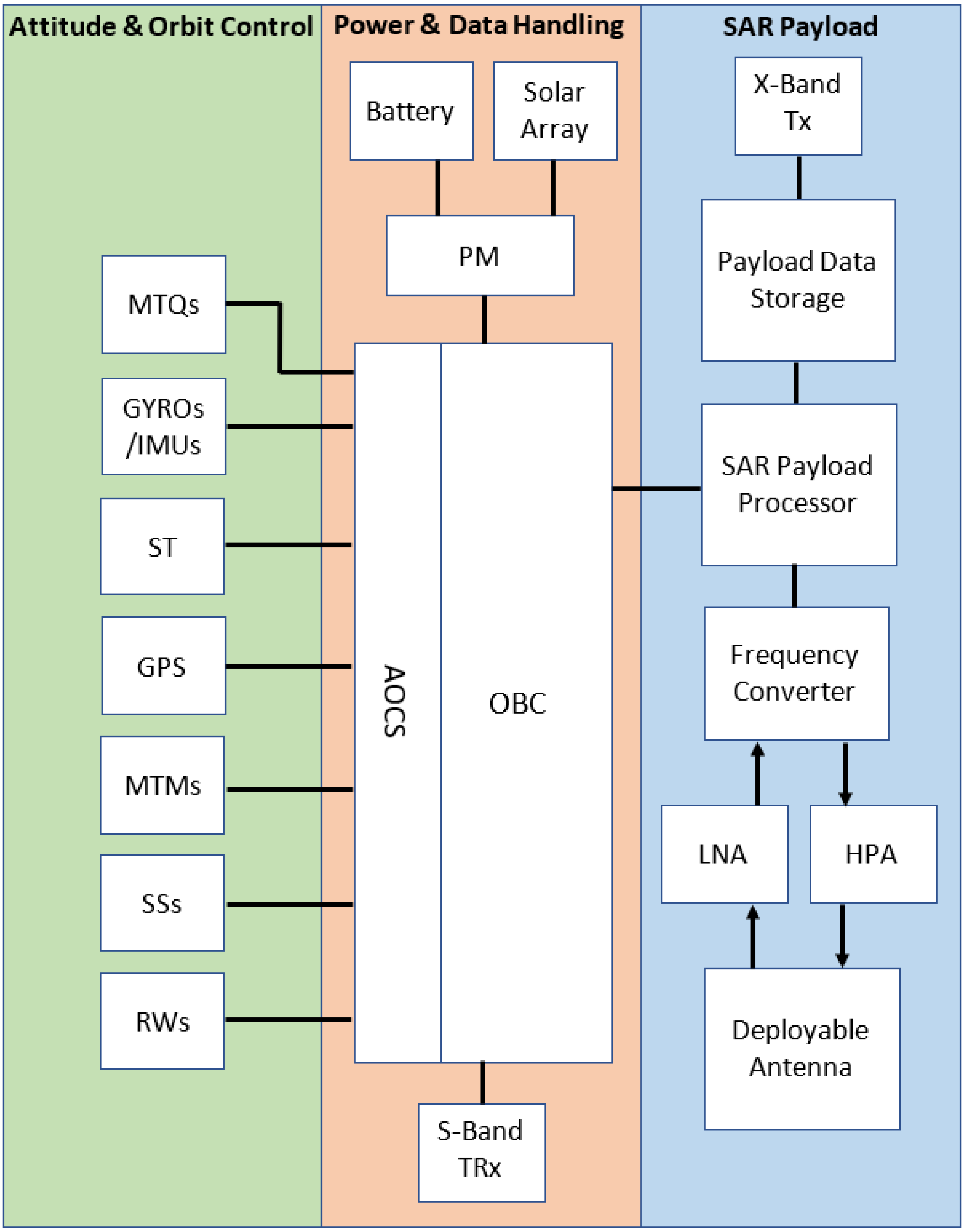

Figure 5-1 Top-level satellite architecture required by SAR payload

6 Top level Platform/Mission Description

The platform/mission needs to provide the following functions:

6.1 Orbit

- The current generations of SAR constellations operated by ICEYE and Capella Space have their spacecraft in 570 and 500 km, sun-synchronous orbits respectively [7] [3].
- As the resolution of SAR images is directly related to the altitude of the orbit, the lower the spacecraft is, the higher resolution that can be achieved. Coupling this with the wide range of launch vehicles that can place spacecraft in sun-synchronous, ~ 500 km orbits explains the orbit choice for these two organisations.
- Sun/Earth-synchronous orbits are also appropriate as they enable regular revisiting of the same locations, with one spacecraft repeating its ground track every 18-22 days for ICEYE [3].

6.2 Platform TT&C

- An S-band transceiver is required for platform TT&C, as employed by ICEYE's spacecraft [3].
- A separate X-band transmitter is required for the downlink of the SAR payload data. This would likely be included as part of the payload for the OSSAT as it is not required by the platform.
- SSTL's CARBSAR will have a downlink rate of 500 Mbps for payload data and ICEYE's spacecraft downlinks at 100 Mbps [5] [3]. Capella Space are claiming to be capable of downlinking at 1.2 Gbps but this is likely through the use of two transmitters [13].

6.3 OBDH

- SAR missions generate large amounts of data due to the high frequency and large bandwidth observations. As described in the Payload Description section, for small satellites, trading off the smaller antenna size with higher frequency and therefore higher bandwidth to compensate for the increased noise results in a high data rate from the payload during observations.
- SSTL's CARBSAR is being advertised as having a throughput of 180 GB/day from 45 spotlight mode images, with the data downlinked throughout the day at a rate of 500 Mbps [5].
- The EOS SAR payload operates with a 300 MHz bandwidth and is only capable of imaging for 5 minutes each orbit [4]. Receiving over a wider bandwidth increases the data generated when imaging. The imaging time is however primarily limited by the very high power requirement of SAR payloads which means that the batteries have to be recharged after a short period of operation.
- The ICEYE spacecraft can only conduct continuous imaging for 120 secs/orbit at a bandwidth of 300 MHz [8].

6.4 Attitude and Orbit control

- Accurate attitude control is required for the *Spotlight* mode of operation (See the Nominal Operations section below for a description of the different modes). This mode involves the antenna beam being pointed at the imaging location and held there to increase the illumination time on the target. Current SAR payloads use electronic beam steering to do this tracking manouevre rather than physically slewing the spacecraft. Accurate attitude control is still required for this technique to keep the spacecraft's attitude stable whilst the antenna beam is electronically steered.
- Pointing accuracy of < 0.1° is required for the *Spotlight* mode even if using electronic beam steering for the reasons explained above. ICEYE's platform from York Space Systems has a pointing accuracy

of 10-36 arcsecs [9]. This platform also provides a stability of 0.25 arcsec/s. Unless an antenna pointing mechanism is used, accurate pointing will also be required for the X-band payload data downlink regardless of the imaging technique used.

- The SAR mission proposed in [2] states that a pointing accuracy of ± 0.1° is required for SAR imaging with an attitude determination accuracy of < 0.25 °. The platform stability required is also of the order of 10^{-4} °/sec [2, p. 166].
- A GPS unit is required to provide the SAR transceiver with a PPS signal. The GPS unit is also required for accurate orbit determination to improve the geolocation accuracy of images. See the Payload Commissioning section below.

6.5 Power

- SAR payloads generally have an extremely high power requirement which is the key reason that SAR satellites can only image for a few minutes each orbit.
- A SAR payload proposed by members of the Japan Aerospace Exploration Agency (JAXA) is stated to require 1100 W of DC power [14, p. 14].
- Although a value for DC power requirement for Cappella Space's payload is not available, their solar panels are capable of generating 400 W which they claim will allow them to image for 10 minutes per orbit [13].

6.6 Thermal

- As SAR payloads have an extremely high DC power requirement and RF chains are generally only 30-40 % efficient, a large amount of heat will be produced by the payload. The key challenge will therefore be to remove this excess heat, produced during imaging.
- The JAXA-proposed small satellite SAR payload is predicted to produce ~700 W of heat during operation [14, p. 15]. This paper proposes using a 50x40 cm, 5 kg aluminium plate to act as a radiating surface.
- A paper proposing a small satellite SAR payload states that an average of 1000 W of heat will be generated during operation of the payload. This paper proposes using a thick aluminium plate as a radiating surface. This will experience a temperature rise of 50° during 5 minutes of SAR imaging [12, p. 3886].

6.7 Structure

- A large, deployable antenna is required for synthetic aperture radar missions.
- The ICEYE spacecraft employ a rectangular antenna with a length of 3.25 m [8].
- The EOS SAR payload is available with a circular antenna of 2 – 7 m diameter [4]. See the Payload Description section for the benefits of a larger antenna.
- Capella Space are using a circular antenna of 3.5 m diameter [13].
- The payload will likely have electromagnetic noise requirements. As an OSSAT SAR mission would likely observe in the X-band, the high frequency can result in increased noise in the receiver electronics. The payload would likely require an electromagnetically 'quiet' environment to reduce the noise from the platform. The effect the high RF output of the payload will have on the rest of the platform will also need to be considered.

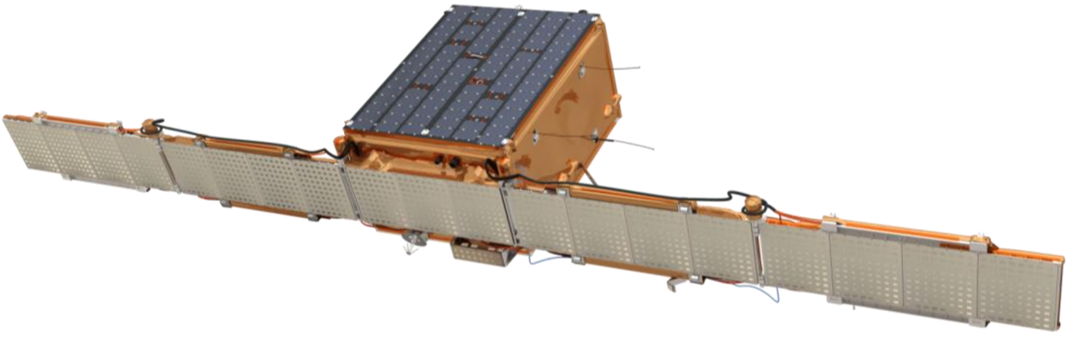

Figure 6-1 ICEYE-X1 First Generation Spacecraft with 3.25 m, deployable antenna [3]

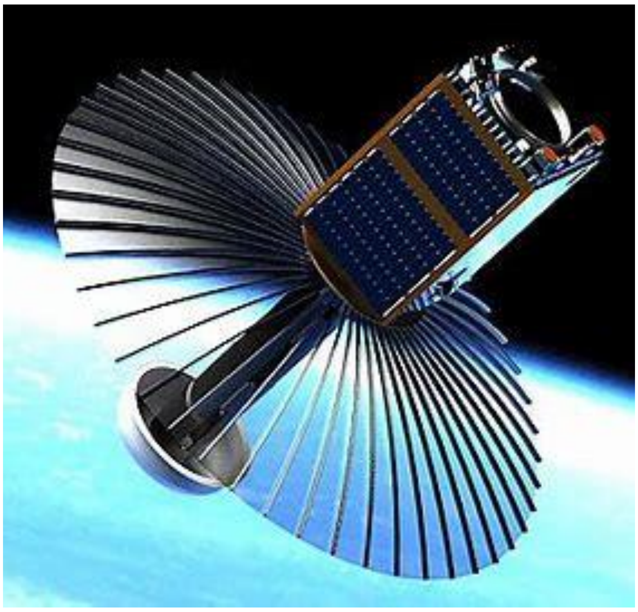

Figure 6-2 SSTL's CARBSAR concept with a deployable antenna from Oxford Space Systems (currently in development) [5]

6.8 Propulsion

- A propulsion system is not required to successfully conduct a synthetic aperture radar mission although some SAR spacecraft have included propulsion on-board.
- The ICEYE spacecraft has electric ion propulsion although this has been included so that the spacecraft can de-orbit at the end of its lifetime [3].

7 Operations Overview

7.1 Pre-launch

- If the platform utilises a propulsion system then this will need to be fuelled during pre-launch operations.
- Functional testing will be carried out to ensure that the satellite is fit for flight. It will then be attached to the launch vehicle separation system.

7.2 Launch and Early Orbit Phase

- The spacecraft will most likely be powered off during launch.
- On separation from the launcher the following activities will have to be undertaken by the platform with respect to the payload:
  - The spacecraft will be detumbled and likely nadir pointed before full 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 include the calibration of the sun sensors, magnetometers, IMUs and the star tracker. Calibration of the sun sensors and magnetometers may be able to be conducted during the initial tumbling of the vehicle.
  - Once nadir pointed the SAR antenna will need to be deployed. This will require some form of pulse/signal to trigger the deployment mechanism.
- As the majority of small satellite SAR missions operate in ~ 500 km, Sun-synchronous orbits, the OSSAT SAR will most likely not need to reach an operational orbit after launch. If the spacecraft is joining an active constellation then a certain phasing with the other satellites may be required. This would require a propulsion system to be included on-board.

7.3 Payload commissioning

- Before payload commissioning can commence, the satellite must be in the following state:
  - The satellite must be detumbled and nadir pointing so that commissioning and calibration of the SAR payload can be conducted.
  - The large SAR antenna must be deployed.
- The satellite platform must do the following to allow the payload commissioning to take place:
  - Contact with a ground station via the S-band will be required for initial payload commissioning and to schedule the calibration activities.
  - A GPS signal must have been acquired to provide the PPS time standard for the SAR transceiver [2].
  - A GPS signal is also required to provide accurate orbit determination so that calibration of the SAR payload can take place. See the initial payload activities description below for more information [3, p. 14].
  - Calibration of the payload will require accurate pointing at known imaging locations.
- The following activities are conducted by the payload before nominal operations can take place:
  - Calibration of the SAR payload is required to correct for imbalances and dispersions within the radar and SAR processor [3, p. 13]. A range of calibration sites are used

around the world which have well characterised isotropic scattering responses so the images generated can be compared with the known geometry of the location.

- Radiometric calibration is required to associate the digital numbers within an image with the mean radar cross section. This compensates for effects due to atmospheric induced delays in the microwave signals and the distribution of radiated energy in the antenna range and azimuth directions [3, p. 14]. During LEOP and regularly throughout the mission, locations with well characterised scattering patterns are imaged to conduct beam calibration and to measure the system noise of the payload.
- Geolocation accuracy is the error associated with the location of a scattering object in an image pixel compared to its true location. These errors are mainly due to uncertainties in the position of the satellite during imaging. Sites with corner reflectors with precisely known geocentric locations are imaged to validate the geolocation accuracy of the SAR mission [3, p. 16].
- Focusing calibration is also conducted by imaging sites with corner reflectors as they act as calibration targets within a pixel. The scattering response from these reflectors is compared to the theoretically expected performance and the payload is calibrated accordingly [3, p. 17].

7.4 Nominal operations

- Payload On/Off Times:
  - SAR payloads are not on all of the time. They are turned on for specific imaging events due to their high power requirements. The times at which the payload will be on will be determined by schedule files for imaging events sent during the last contact with a ground station.
  - For small satellite missions the SAR payload is not on for very long each orbit due to the very high power requirement when conducting imaging. For example, ICEYE can only image for 120 seconds continuously each orbit [8].
- The payload command process and format:
  - The specific command format and how these are sent from the platform to the payload is currently unknown.
  - Schedule files for imaging events will be uploaded during ground station contacts which will describe, the position of the imaging target/time of imaging event and the mode the SAR payload should conduct the imaging in.
- The different modes of the payload:
  - SAR payloads commonly have four types of mode that imaging can be conducted in. The amount of modes a single SAR payload is capable of varies depending on the organisation. ICEYE can only conduct imaging in *Stripmap* and *Spotlight* mode with a *ScanSAR* mode in development [3]. The EOS SAR payload has exactly the same capabilities, with a *ScanSAR* mode in development.
  - *Spotlight* mode: A mode which requires the antenna beam to be pointed at a target on the ground and track its location as the spacecraft passes overhead. The mode provides the highest level of resolution possible with a single spacecraft due to the increased illumination time of a single location. A spatial resolution of less than 1 x 1 m is achievable in this mode [3] [4]. This does however reduce to swath width to ~ 5 km [3]

[5]. Physical rotation of the spacecraft is not be required for modern SAR payloads as electronic beam steering can be used instead, as ICEYE do [3].

- *Stripmap* mode: The antenna beam is held in a fixed elevation to transmit a continuous series of pulses to image a strip of surface parallel to the satellite's ground track. This results in a decreased resolution but increased swatch width (up to 30 km for ICEYE [3]). The antenna beam is not held in a nadir pointing position for this mode. It is pointed at a constant angle with respect to the local vertical and the pulse bandwidth is selected specifically depending on this angle [2] [3]. E.g. for Stripmap mode, ICEYE point the antenna at an angle of 15 – 30° off nadir [3, p. 18]. The resolution of the images generated in this mode is directly dependent on the size of the antenna [3]. The platform itself can be nadir pointed for this mode as the elevation of the antenna beam can generally be controlled electronically [2] [3, p. 19].
- *ScanSAR* mode: The ScanSAR mode improves the swath width of the payload by varying the incidence angle of the antenna beam. The beam is swept across the spacecraft's track, reducing the resolution of the images but increasing the area covered during a single imaging event. This method is complex to implement and therefore is in development for both ICEYE and EOS SAR [3] [4]. The cross-track pointing of the antenna beam could be done physically by the spacecraft rotating or through electronic beam steering. It is assumed that beam steering will be used by organisations such as ICEYE as they utilise this technique for their other imaging modes already [3, p. 18].
- An interferometric mode could also be employed. Neither ICEYE or Capella Space currently have this capability. It requires two or more spacecraft to image the same location at the same time and therefore requires a well-populated constellation. See the Payload Description section for more information.

- Payload On/Off Sequence of Events:
  - The sequence of events required to turn the payload on and off are currently unknown.
- During payload operation, the following platform units will need to be activated:
  - During Imaging, electronic beam steering is generally used to point the beam at different locations. Despite the fact that spacecraft does not need to slew to conduct imaging, a stable and accurately controlled platform will still be required so that the electronic beam steering can precisely point at the imaging locations.
  - For a Spotlight imaging mode, all of the AOCS components required to provide the < 0.1° attitude control and high stability will need to be in operation (e.g. star trackers, gyros, etc.).
  - The Stripmap mode may not require such accurate attitude control as the Spotlight mode as the antenna beam is held at a fixed elevation and scans a strip of the Earth parallel to the spacecraft's ground track. The attitude control requirements for each imaging mode would have to be checked as this would drive which AOCS components are required to be powered on during imaging.
  - The GPS unit will need to be turned on during imaging to provide an accurate location of the spacecraft to improve the geolocation accuracy of the images. See the description of the payload calibration above.
- Payload pointing:

  - Current SAR payloads use electronic beam steering to point at different imaging locations. The platform therefore only needs to provide nadir pointing for the payload antenna. It would however need to provide a stable and accurately controlled platform so that the beam pointing is precise.
  - Due to the large amounts of data generated in SAR missions (See the Platform Description), pointing of the X-band transceiver at ground stations may be required to achieve the required downlink data rate.
  - Because the pointing of the antenna beam is not provided by the platform, there are likely to be no stringent requirements on the platform needing a high slew rate.
- Inter-Satellite Communications:
  - Inter-satellite communications are not required for a SAR mission.
- Orbital Manoeuvres:
  - No orbital manoeuvres are required during the normal operations of a SAR mission.
- Payload Deployables:
  - A large antenna will need to be deployed by the platform. See the Payload Description section for a description of the types and sizes of antenna most commonly used.
- Payload Time Requirements:
  - The payload requires a PPS signal from the GPS unit to act as the local oscillator for both the transmission and reception of signals. See the Payload Description section for more information.
- Payload Attitude/orbit data:
  - It is likely that the spacecraft's position will need to be passed to the SAR processor so that the antenna beam can be accurately pointed at imaging locations and increase the geolocation accuracy of the generated image.

7.5 ICD Questions

- Payload Mass/Volume:
  - SAR payloads are generally quite large. The EOS SAR payload is 50 kg with a 7 kg, 3.5 m antenna [4]. The SAR payload that will be flown on-board SSTL's CARBSAR is ~ 50 kg (deduced from total spacecraft mass and mass of Carbonite platform) [5].
  - The payload masses of ICEYE and Capella Space are not known but the total spacecraft masses are 85 and 40 kg respectively.
  - Detailed descriptions of the available SAR antennas are given in the Payload Description section.
- Payload position on platform:
  - The SAR payload will likely need to have an electromagnetically 'quiet' environment to reduce noise in the receiver generated by the platform.
- Payload Temperature Requirements:
  - The temperature requirements of typical SAR payloads are currently unknown.
- Payload power, data storage and downlink requirements:
  - SAR payloads are likely to have quite high power requirements. See the Platform Description for more information.

- A high level of data storage will be required for a SAR payload due to the large bandwidth that is employed in their observations. See the Platform Description for more information.
- A X-band transceiver is required for the downlink of payload data with SSTL's CARBSAR capable of downlinking at 500 Mbps and ICEYE at > 100 Mbps [3] [5].

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
- Critical commanding
- Recalibration
    - Radiometric re-calibration. During LEOP and throughout the mission, areas with well characterised scattering patterns will be imaged to conduct beam calibration [3, p. 16]. See the Nominal Operations section for more info on the payload calibration.
- 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.
- End-of-mission activities
    - End-of-life activities are considered non-routine operations. See the End-of-Life section below for more information.

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 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 a SAR. However, it will have to be checked with the payload provider that, during an emergency, the payload can be abruptly switched off and that imaging 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

It is not currently known whether any additional FDIR techniques will be required by a SAR payload from the platform.

9 End-of-life operations

If a SAR variant of the OSSAT has a propulsion system on-board then this will need to be passivated at the end-of-life. This would be in accordance with the IADC's debris mitigation guideline stating that the risk of on-orbit explosions and fragmentations of spacecraft should be reduced. If a propulsion system is included on-board then the spacecraft may have to conduct a direct de-orbit or transfer to an orbit with a lower perigee, with a faster decay time. New FCC regulation allows streamlined satellite licensing that costs less if certain requirements are met. One of these is that the spacecraft would deorbit in 6 years, after completing its mission [11].

It will also need to be ensured that the payload transceiver will not transmit signals again in the future.

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