Optical Earth Observation

Concept of Operations

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Revision History

Revision	Date	Comments
1.0	January 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 optical Earth observation (EO) application for the Open Source Satellite. Since this is a generic CONOPs covering an optical EO application, there may be aspects which vary from other specific optical EO applications. If there is a 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	Earth-I blog: Top 5 uses of video from space – why full-colour HD video from space matters	https://earthi.space/blog/uses-of-video-from-space/	01/07/19
2	The International Charter Space and Major Disasters	https://disasterscharter.org/	N/A
3	Planet’s Open Water imaging – Geo Accuracy assessment, 31st Annual AIAA/USU Conference on Small satellites	viewcontent.cgi (usu.edu)	19/06/17
4	DMC-3 eoPortal Directory	https://directory.eoportal.org/web/eoportal/satellite-missions/d/dmc-3	N/A
5	Planet Imagery Product Specifications	https://assets.planet.com/docs/Planet_Combined_Imagery_Product_Specs_letter_screen.pdf	06/20
6	SkySat eoPortal Directory	https://directory.eoportal.org/web/eoportal/satellite-missions/s/skysat	N/A
7	RapidEye eoPortal Directory	https://directory.eoportal.org/web/eoportal/satellite-missions/r/rapideye	N/A
8	Spot 6-7 eoPortal Directory	https://earth.esa.int/web/eoportal/satellite-missions/s/spot-6-7	N/A
9	From Satellite Launch to Product Launch: A Behind the Scenes Look	https://medium.com/planet-stories/from-satellite-launch-to-product-launch-a-behind-the-scenes-look-cccfce40dce8	23/01/20
10	Kestrel Eye Block II SmallSat Conference Paper.	32nd Annual AIAA/USU Conference on Small Satellites paper https://www.researchgate.net/publication/327510322_Kestrel_Eye_Block_II	09/2018
11	SpaceFlight Now article: SpaceX rideshare provides new path to orbit for BlackSky	https://spaceflightnow.com/2020/06/26/spacex-rideshare-provides-new-path-to-orbit-for-blacksky/	26/06/20
12	Fierce Electronics article: Largest Flock of Earth-Imaging Satellites launch into Orbit from Space Station	https://www.fierceelectronics.com/components/largest-flock-earth-imaging-satellites-launch-into-orbit-from-space-station	13/02/14
13	ECAPS High Performance Green Propulsion	https://www.ecaps.space/hpgp-proven-in-space.php	N/A

RD-#	Title	Document Location	Date
14	Bradford Space Comet Water-based propulsion for small satellites	https://www.bradford-space.com/assets/pdf/be_datasheet_comet_2019oct.pdf	N/A
15	Planet Labs Specifications - Spacecraft operations and Ground systems	Daily Satellite Imagery and Insights | Planet	Vr 1: 06/15
16	Planet eoPortal Directory	https://directory.eoportal.org/web/eoportal/satellite-missions/p/planet	N/A
17	Commissioning the World's Largest Satellite Constellation, SSC17-X-03	31st Annual AIAA/USU Conference on Small Satellites [Paper Number] (usu.edu)	2017
18	Calibration Test Sites Selection and Characterisation – WP210	Microsoft Word - CALIB-TN_WP210-GAEL_ETHZ_001.doc (ceos.org)	2008

1.4 Acronyms and Abbreviations

The following abbreviations are used throughout this document:

ADCS	Attitude Determination and Control System
AOCS	Attitude and Orbit Control Sub-system
APM	Antenna Pointing Mechanism
ASS	Sun Sensor
BATT	Battery
BCR	Battery Charge Regulator
CCD	Charge Coupled Device
CCSDS	Consultative Committee for Space Data Systems
CMG	Control Moment Gyro
CONOPs	Concept of Operations
COP	Communications Operation Procedure
DEM	Digital Elevation Model
EM	Electro Magnetic
EO	Earth Observation
FDIR	Failure Detection Isolation and Recovery
FPA	Focal Plan Assembly
FOV	Field Of View
FTP	File Transfer Protocol
Gb	Gigabytes
GPS	Global Positioning System
GSD	Ground Sampling Distance
HPGP	High Performance Green Propellant
IADC	Inter-Agency Space Debris Coordination Committee
IMU	Inertial Measurement Unit
ISL	Inter-Satellite Link
LAN	Local Area Network
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
LTAN	Local Time of Ascending Node

LTDN	Local Time of Descending Node
Mbps	Mega bits per second
MEMS	Micro-ElectroMechanical System
MLI	Multi-Layer Insulation
MSI	Multi-Spectral Imager
MTF	Modular Transfer Function
MTM, Mag	Magnetometer
MTQ	Magnetorquer
OAP	Orbit Average Power
OBC	On Board Computer
OBDH	On Board Data Handling
OSSAT	Open Source Satellite
PCM	Power Control Module
PDM	Power Distribution Module
PPS	Pulse Per Second
RF	Radio Frequency
RMS	Root-Mean-Square
Rx	Receiver
RW, WHL	Reaction Wheel
SNR	Signal-to-Noise Ratio
SSO	Sun Synchronous Orbit
STAR	Star Tracker
TT&C	Telemetry and Telecommand
Tx	Transmitter
UHF	Ultra High Frequency

2 Mission Objectives and Overview

Earth Observation (EO) is a generic term for any satellite mission that gathers information about the Earth. This is a very broad definition, which encompasses many different specific applications with different Concepts of Operation (CONOPs). This document will focus on passive electro-magnetic radiation imaging EO missions, using PAN, Multispectral and video imagers.

EO missions with these types of imagers are used for a multitude of applications such as:

- Disaster monitoring – floods and fires
- Crop monitoring – vegetation coverage
- Environmental monitoring – land use change such as illegal logging
- Urban Planning – Housing needs and monitoring road/car park usage

The use of colour video from space provides richer data that can be used to generate more accurate Digital Elevation Models (DEMs) which can be used to more easily detect change and can allow the detection of movement (cars, planes and military vehicles) to be made more readily [RD-1]. An additional benefit of video is that it mitigates to some extent cloud cover, as imagery can be captured between the clouds.

EO missions take place in Low Earth Orbit (LEO) to allow higher resolution images to be taken without the need for extremely large instruments. This results in limited time over targets, a latency in data or long times between revisits of the same area. This is addressed by the use of satellite constellations, either of identical satellites operated by one operator, or a consortium of different satellites that can be combined in times of need to generate frequent images of areas, such as used by the International Charter 'Space and Major Disasters' [RD-2].

PAN and Multispectral imagers (MSI) also require 'good' illumination in order to provide quality imagery. This results in the majority of EO satellites being used in a Sun-Synchronous Orbit (SSO), with a fixed Local Time of Ascending Node (LTAN). The LTAN can be selected depending on the purpose and payload of the mission. Payloads operating in the visible region of the electromagnetic (EM) spectrum tend to use an LTAN of around 10:30am (or the equivalent 22:30 Local Time of Descending node (LTDN). This allows shadows to provide an inference of height, and also provides a statistically better chance of clear weather for the images. Being in a sun-synchronous orbit also allows the target to always be viewed with the same conditions, which is beneficial for change management.

However, if intensive imaging is required over a confined area, such as the equatorial belt, a lower inclination orbit may be selected. This has the issue of not being sun-synchronous and therefore illumination conditions can vary significantly. Having a constellation of satellites can be employed to reduce this impact.

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

Capability	Performance	Note
Reference Orbit	SSO (Sun-synchronous Orbit) Altitude = 450-700 km LTAN range = 09:30 to 11:30 LTDN range = 21:30 to 23:30 Examples: • Skysat: 400km [RD-6] • Triplesat: 651km [RD-4] • Doves: 420km (low inclination)/475km (sun synchronous) [RD-9]	Ranges for altitude and LTAN/LTDN may extend a bit further in some cases, but this reduces the quality of the imagery. Altitude can go down to 300km, but this causes lifetime issues as the impact of atmospheric drag and therefore rate of orbital decay increases.
Spacecraft Type	CubeSats to small satellites of several 100s of kg. Examples: • Doves: 5kg (SuperDoves may be slightly heavier) [RD-9] • Skysat: 110kg: 110kg [RD-6] • BlackSky: 55kg [RD-11] (uses LeoStellar bus) • Carbonite-2: 100 kg • RapidEye: 156kg [RD-7] • TripleSat: 447kg [RD-4]	The type is driven by the capability and performance needs of the payload in terms of resolution, focal length and MTF (for optical), which is determined by the precise application that the satellite is servicing.
Spacecraft Design Life	5-7 years for small satellites. CubeSats typically have a shorter lifetime. Examples: • Skysat: 6 years (Image & video satellite) [RD-6] • TripleSat: 7 years [RD-4] • Planet Doves: 1-3 years [RD-9]	A lifetime of 5-7 years is normally typical of satellites larger than a CubeSat. Nanosats have shorter lifetimes but they are readily replenished to ensure that the constellation is operational over a longer period.
Spacecraft Agility	This will vary depending on craft and application and will vary from Nadir only to rapid off-pointing. Off axis pointing of up to 40-45° can occur for some missions. Examples: • Planet Doves: None/limited agility [RD-9] • SkySat (later models): off-point [RD-6] • TripleSat slew rate: 30° in 40s [RD-4] • RapidEye: ±20° off pointing (slew rate unknown) [RD-7]	The agility of an EO satellite depends on the application that the satellite is designed for and its operations. For example, Planet Doves only point nadir and are always imaging whereas other satellites image targets and only gather data at these times. Slewing is also required for video capture, such that the satellite stares at a fixed point on the ground. The rate of this slew is dictated by the altitude of the orbit.
Pointing Accuracy	Examples:	Depends on the operational mode and

Capability	Performance	Note
	• Planet Doves on average have been measured to be 0.1° (2σ), in roll/pitch and yaw [RD-3] • Skysat: ±0.1°, without star tracker [RD-6] • TripleSat: Pointing accuracy knowledge: 72 arcsec, Pointing accuracy control = 360 arcsec [RD-4]	the resolution of the imager. Skysat had an issue with their star trackers which was resolved on orbit. The star trackers now have a performance of <7arcsec RMS cross boresight and <70 arcsec RMS around boresight [RD-6].
Pointing Stability	Examples: • TripleSat: Pointing stability= 2 arcsec/s [RD-4]	Stability will drive the selection of AOCS units A satellite’s pointing proficiency is usually defined in terms of accuracy and stability. Accuracy is quantified in degrees indicating how far off from the intended target the pointing is measured. Stability refers to how well the satellite maintains that pointing accuracy, quantified as a standard deviation from the accuracy. One application, for example, might require 1 degree of accuracy with a stability of 0.1 degree in one standard deviation
Onboard Data Storage Requirement	Examples: • Skysat: 360Gb redundant storage [RD-5] • TripleSat: 128Gb redundant non-volatile storage [RD-4]	
Communications	Generally X-band is used for payload downlinks due to the amount of data. Examples: • Planet: up to 200Mbps [RD-3] • Skysat: up to 580 Mbps [RD-5] • TripleSat: up to 400Mbps [RD-4]	The rate varies depending on the amount of data that is collected.
Payload Thermal	A stable thermal environment must be maintained by reducing thermal gradients across the imaging barrel and keeping the payload within its tolerances.	See section 6.5 for more information.
Payload Power	Highly variable. Dependent on a number of factors including platform size and desired resolution.	
Propulsion Requirements	Not required for the nominal operations of an EO satellite.	See section 6.7 for more information.

Table 2-1 Top-level objectives/capabilities of a satellite conducting an Optical EO mission

3 Mission Architecture

For optical EO the specific application drives the operational mission architecture, and generally relates to the latency of the data.

There are two main types of mission operations which will be described in more detail in Section 7: targeted image capture and strip image capture.

- Targeted image capture is when an image is taken of a specific place, as requested by the customer (e.g. TripletSat, Skysat).
- Strip Image capture is where assets image large strips of land to build up a database of imagery that people can request from a catalogue (e.g. Planet Doves)

Depending on the operator, they may either own the TT&C and payload ground stations (which may be co-located), or they may rent the payload ground stations (especially if several ground stations are utilised to get data down with lower latency).

Figure 3-1 shows a simple architecture for an optical EO mission. Figure 3-2 shows an optical EO mission architecture with multiple payload ground stations.

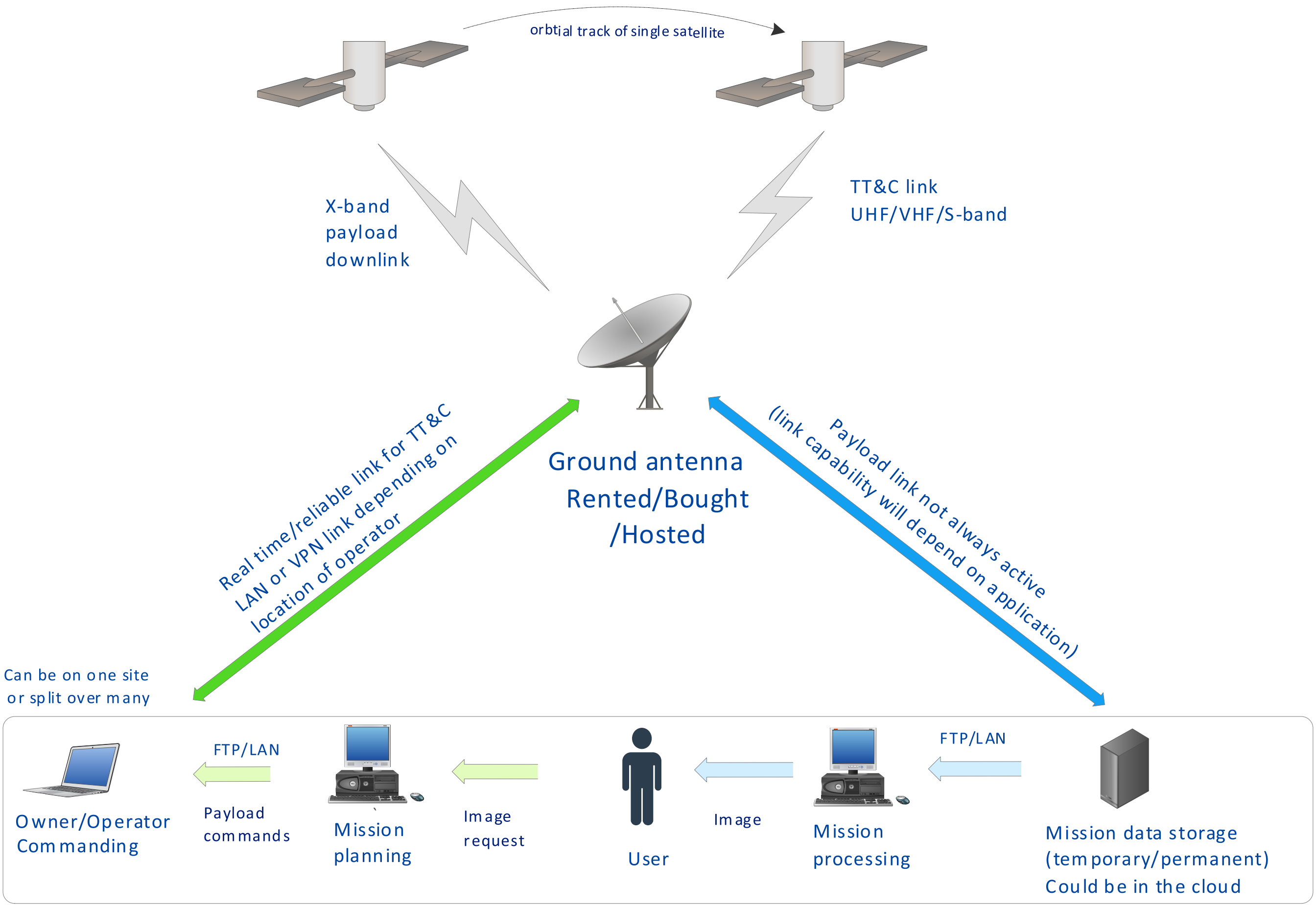


Figure 3-1: Simple Optical EO Mission Architecture

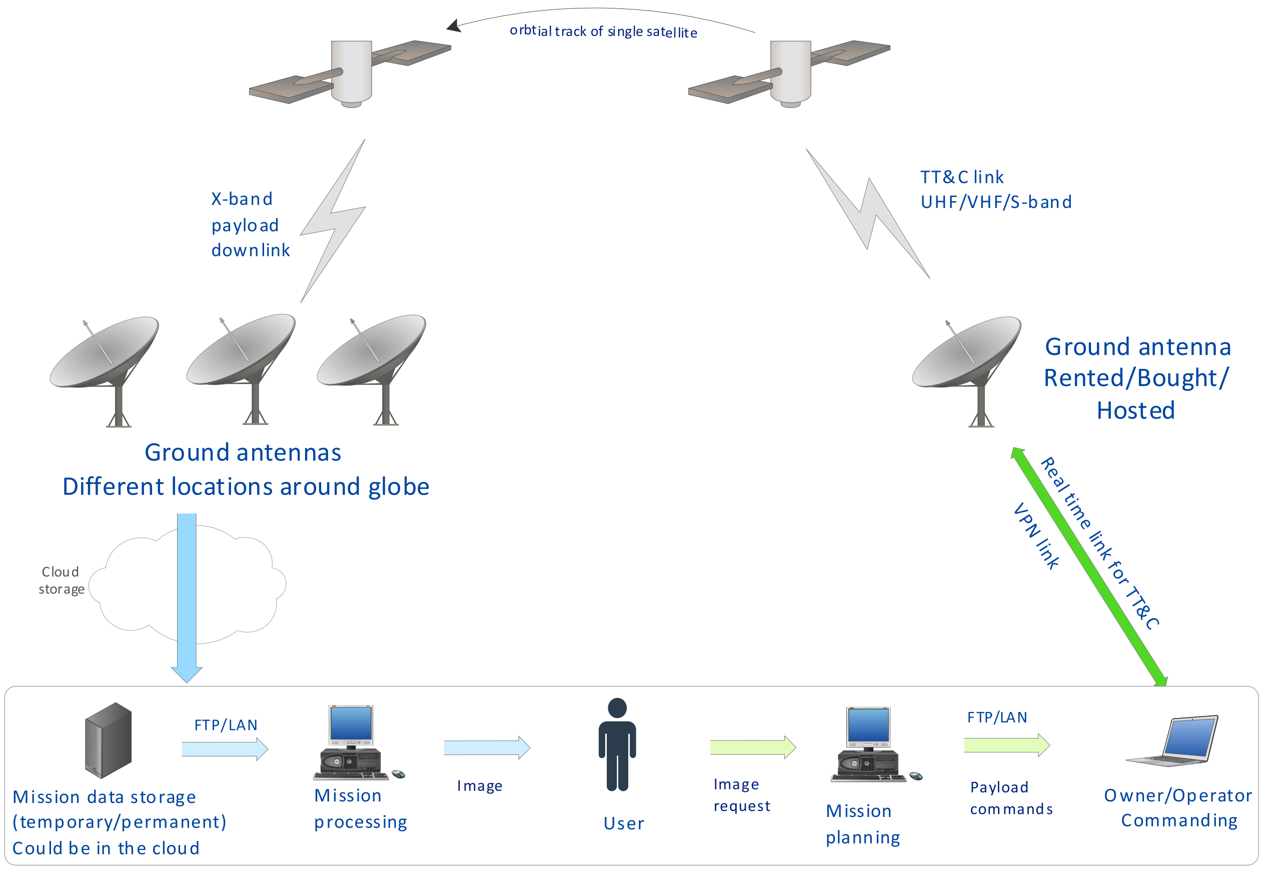


Figure 3-2: Multiple payload ground stations mission architecture for Optical EO

4 Top level Payload Description

A typical EO payload consists of several discrete functions, as can be seen in Figure 4-1 below.

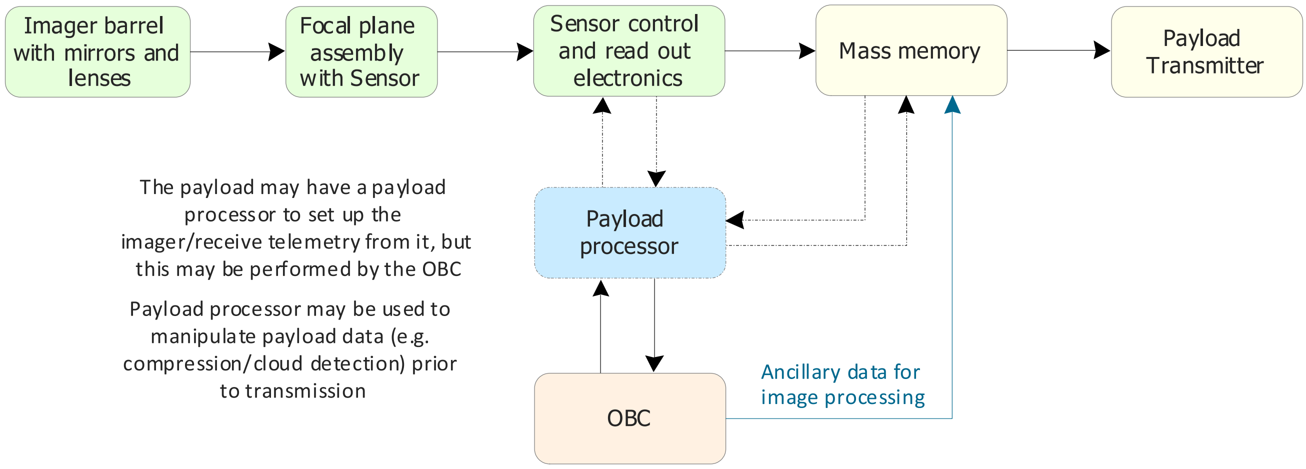


Figure 4-1: Payload block diagram

The largest physical part of an EO payload tends to be the light capturing system which will vary in size depending on the altitude of operation, the ground sampling distance (GSD) and the signal-to-noise (SNR) requirements. The optics gathers the light that falls on the payload sensor. This sensor can be either a strip or an area charge-coupled device (CCD), depending on the mode of operation of the payload and the products that it is producing.

The sensor sits in the focal plane assembly (FPA), which is used to align the position of the sensor with respect to the optics. The electronics attached to the sensor 'reads-out' the charge and therefore signal from the sensor. They also control the image capture set up, such as exposure time, integration time and drive voltages for the CCD. These parameters can be passed to the control electronics from either a payload processor or directly from the on-board computer (OBC).

Once data has been read-out, it is passed to a memory storage area to hold it until it can be downlinked to the ground. In some instances, the data rates from the imager are so high that volatile memory storage is required to keep up. The data is then passed to non-volatile memory in slower time for longer term storage. Depending on the mission, a payload processor may perform manipulation of the data on-board prior to downlinking. This can involve compression or cloud detection on imagery and is generally used to reduce the amount of data that is transmitted to the ground. With more data being generated, data manipulation and processing will become more important.

When the satellite is over the ground station, the payload transmitter, generally at X-band, is used to send data. This frequency band is used due to the large amount of data that needs to be downloaded. Rates up to 580 Mbps have been achieved. Future satellites may look at going to even higher frequencies such as Ka/Ku band. On some missions, this route may be used to pass platform telemetry so that the state of health of the satellite can be determined even on passes where no TT&C link is used.

To aid in the payload data processing, ancillary data may be stored with the payload data, either as additional information in the image file, or as separate files. This may include information about the imager settings (e.g. exposure time etc), the attitude of the satellite and the exact time of the image capture.

5 Satellite Architecture

Figure 5-1shows the top-level satellite architecture for a RapidEye satellite which is an example of a mid-resolution EO satellite [RD-7]. Figure 5-2 and Figure 5-3 provide more detail on the attitude and orbit control system (AOCS) solution for RapidEye.

See section 1.4 for definitions of the acronyms and abbreviations used in the following diagrams.

Five RapidEye satellites were flown in a constellation, providing 6.5 m resolution imagery in 5 bands. Each satellite had off-pointing capability up to ±20°. The satellite would remain in a course nadir pointing attitude, until the time of an image capture, at which point the star tracker would be turned on and a fine-pointing nadir attitude mode entered.

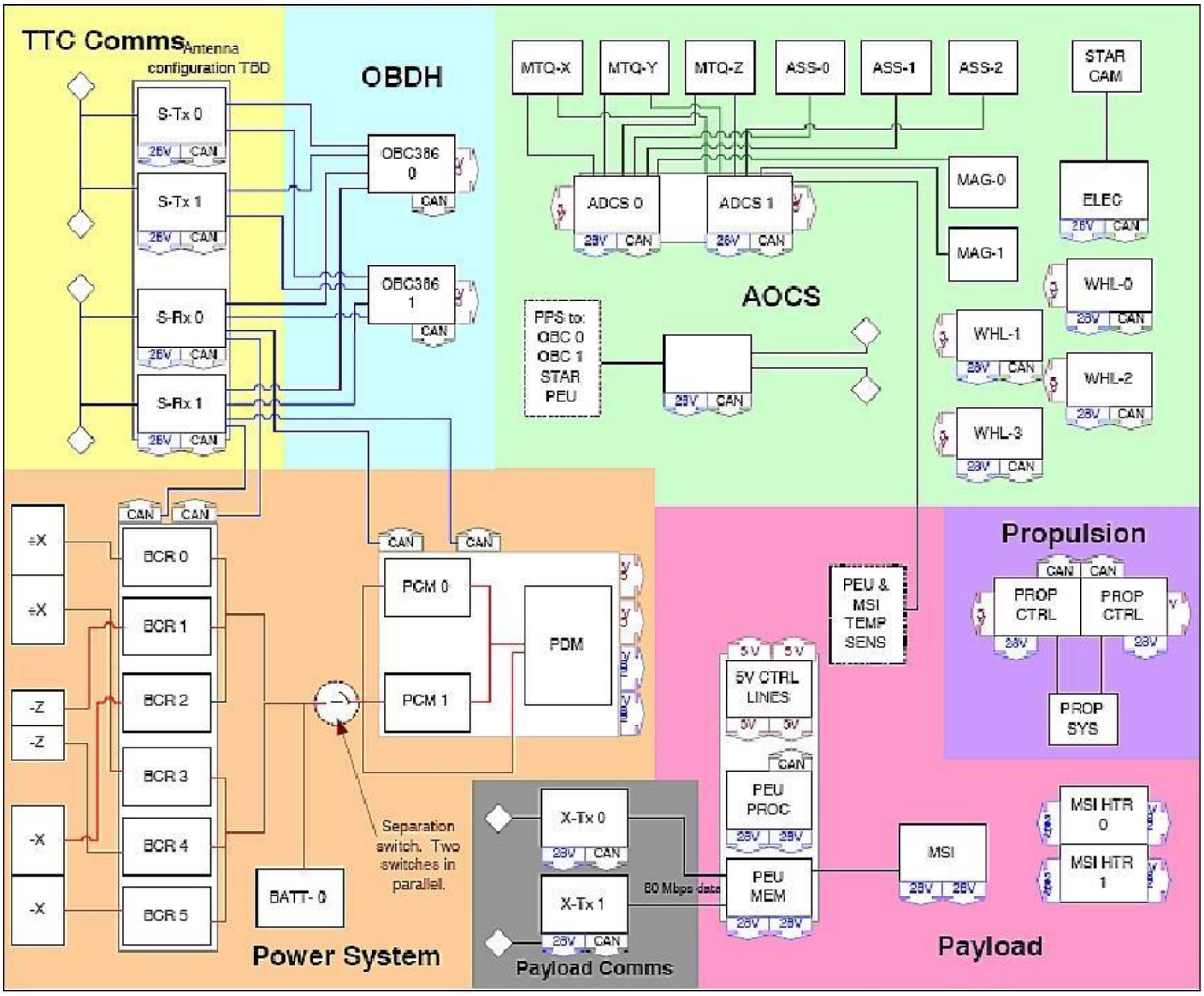


Figure 5-1: RapidEye satellite architecture [RD-7].

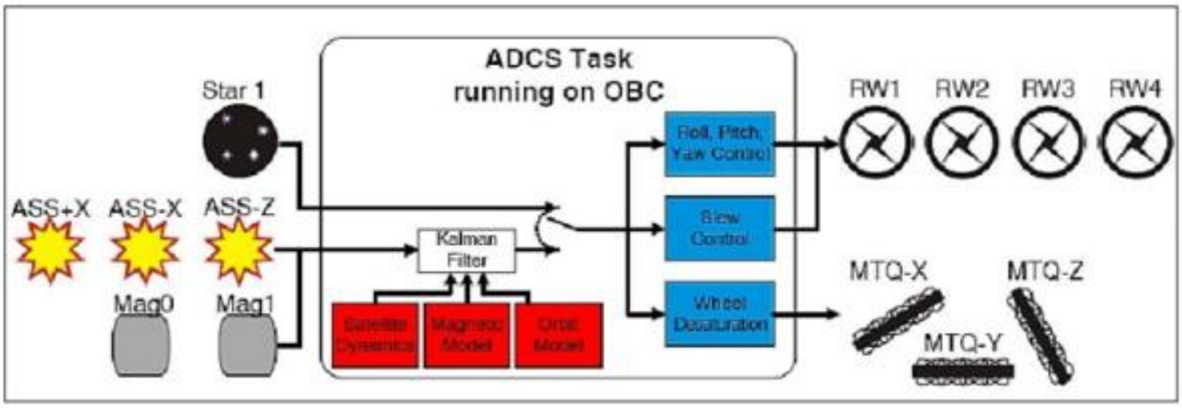


Figure 5-2: RapidEye attitude, determination and control (ADCS) software architecture [RD-7].

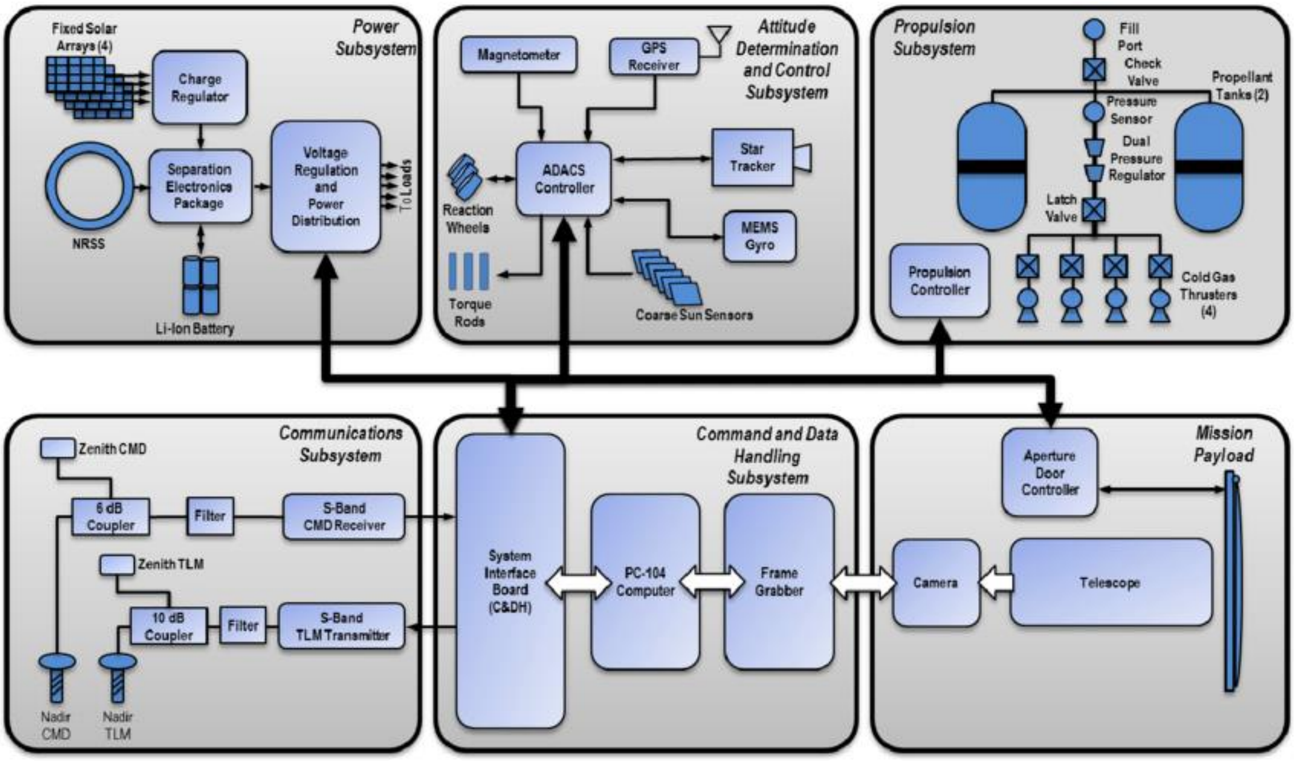


Figure 5-3: RapidEye AOCS functional architecture [RD-7].

Most EO satellites will have similar architectures with star trackers and gyroscopes becoming more common to provide high accuracy pointing and rapid slew capability. Even the Planet SuperDoves have rate gyroscopes and star trackers, alongside magnetometers, magnetorquers and reaction wheels.

Figure 5-4 provides another example of an optical EO architecture, in this case for the Kestrel Eye satellite.

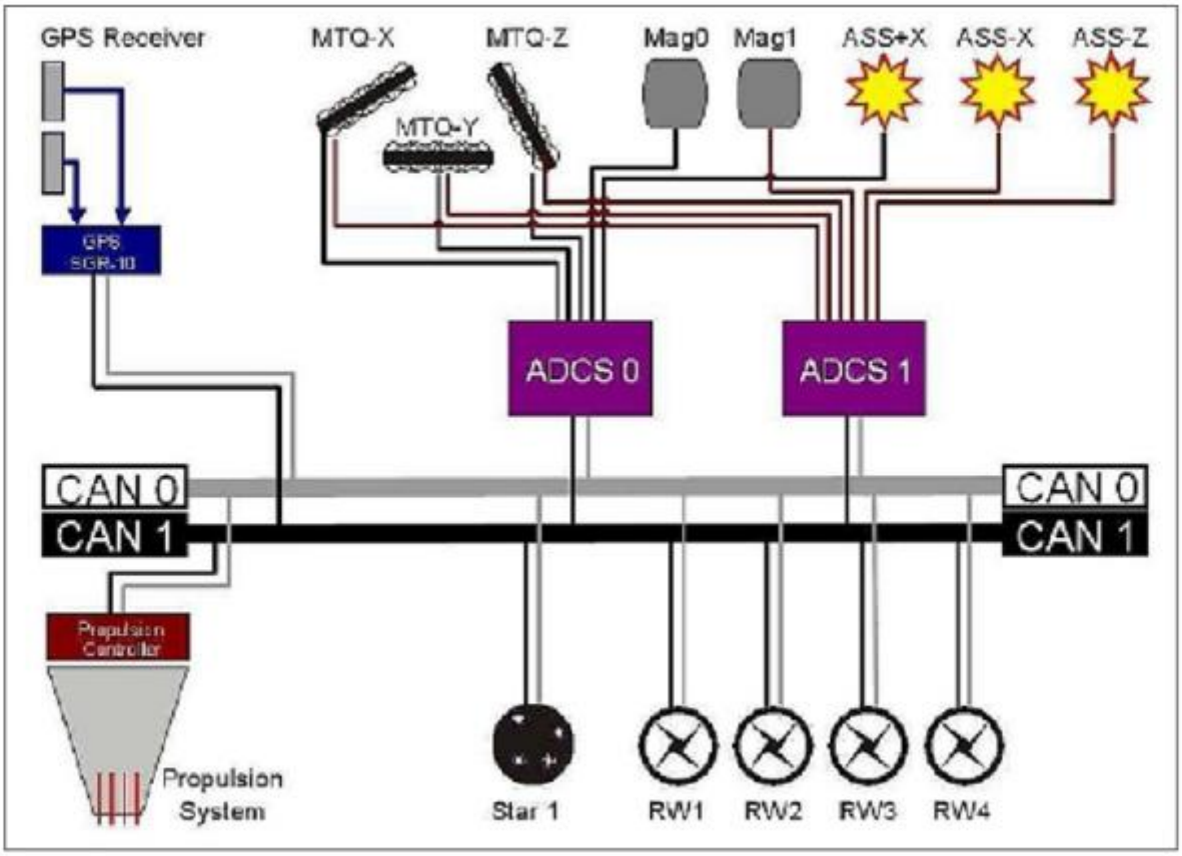


Figure 5-4: Kestrel Eye Satellite Architecture [RD-10].

Larger satellites may use control moment gyroscopes (CMGs) when fast slews are needed but these are generally not used for smaller craft, due to the volume restrictions. Spot-6 is an example of such a spacecraft utilising CMGs as it required a slew rate of 30° in 12 seconds, for a 720 kg satellite [RD-8].

Taking the simplest and most complicated architectures a generic architecture can be generated, as shown in Figure 5-5. The number of sensors and actuators depends on the level of redundancy required by the customer and mission requirements.

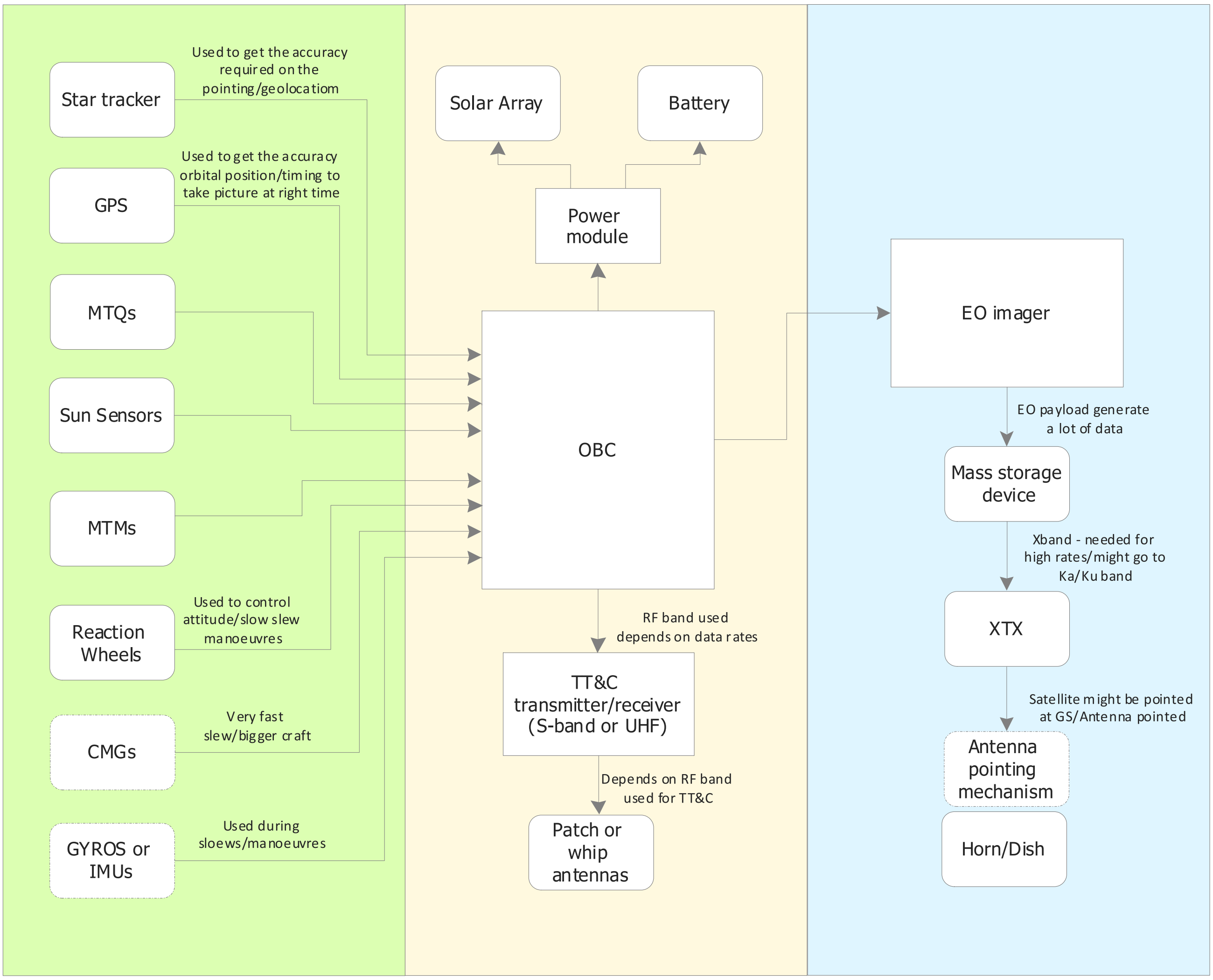


Figure 5-5: Generic optical EO satellite architecture.

6 Top level Platform/Mission Description

The platform/mission needs to provide the following functions:

6.1 Platform TT&C

- Generally, EO satellites make use of either ultra-high frequency (UHF) or S-band TT&C systems. These use either a deployable whip antenna arrangement for the UHF system or patch antennas for the S-band.
- UHF TT&C systems tend to operate at a lower data rate than the S-band systems. This can be an issue if software uploads are required, or if the TT&C system is used to back-fill holes in payload data. The impact of the need to upload new software to satellites depends on the availability needs of the satellite, the size of the software upload and the speed of the uplink.
- Some protocols allow missing packets to be re-requested and downloaded again to ensure that a complete payload data file is always received (E.g. COP-1 under CCSDS).

6.2 OBDH

- The platform OBDH system is comprised of the OBC required to control the satellite and provide commands to the payload. The type of OBC required is heavily influenced by the complexity and speed of the attitude control loops. For more agile craft, the rate of the attitude loops needs to increase to several Hz which has implications on the processing capability of the OBC. Processor types being used in the market include LEON3, OBC 750s, etc.

6.3 Attitude and Orbit Control

- The AOCS (Attitude and Orbit Control Subsystem) has a key role in EO satellites. This sub-system has the following functions:
    - Control and knowledge of attitude pointing
    - Attitude stability
    - Jitter control

  and where applicable control of orbital parameters and phasing with other satellites in a constellation.
- EO AOCS systems usually consist of:
    - Star tracker
    - Global Positioning System (GPS) Receivers
    - Magnetometers
    - Sun sensors
    - Gyroscopes
    - Magnetorquers
    - Reaction Wheels
- Gyros were initially used on more agile craft during slewing. However, as these components have shrunk and reduced in cost significantly with the use of micro-electro mechanical (MEMs) technologies they are being employed even on small satellites (E.g. Planet SuperDoves [RD-9]) for rate control within a stellar-gyro system.
- Depending on the lifetime of the mission, the components can either be in a redundant architecture, or single string. For reaction wheels, redundancy is generally reached through the use of 4 wheels in a tetrahedral arrangement. The use of MEMs gyros, which tend to have a lower accuracy and higher

drift rates can lead to the need to have multiple gyros on at any one time (for example 2 gyros in the primary chain and 2 gyros in the redundant chain).

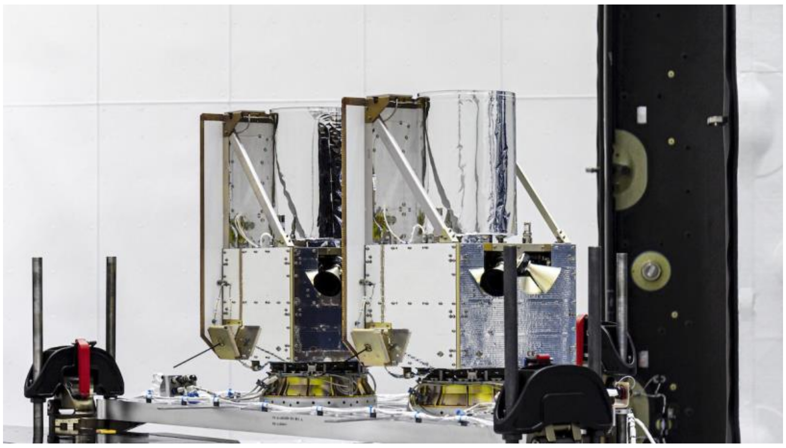
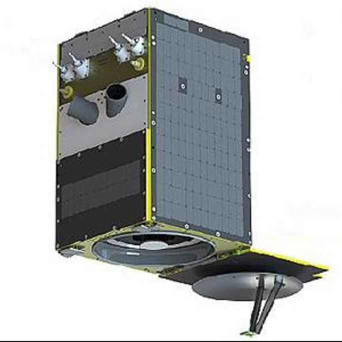
- As the capability of EO payloads increases the demand for better resolution imagery increases and that puts tighter requirements on the AOCS system, not only from the positional aspect but also from the stability aspect.
- Generally, a higher resolution payload will have a narrower swath width. For satellites that operate in a 'targeted image capture' mode, this translates into a need for more accurate targeting of the required ground point. This drives not only tighter pointing needs on the craft but also tighter timing and orbit knowledge and control to ensure that the picture is taken at the right point. This results in the need for good GPS, Star trackers and control loops that operate at sufficient speed to maintain accurate pointing.
- In addition to this, higher resolution results in a demand for greater stability from the craft whilst the image is being taken. With smaller pixel sizes on sensors being used to obtain this high resolution imagery, small movements (for example resulting from jitter, micro-vibration or slow frequency wobble from the control system) on the satellite can translate to large movements of the ground position. If these are too large, they can result in blurry images. In order to reduce micro-vibration, isolation of any mechanisms that are operating during imaging needs to take place.
- Star trackers provide the most accurate attitude knowledge of the sensors and are used for accurate pointing and geo-location (position of the taken image to the requested position). As the key aspect of EO systems is to control the pointing of the camera, many satellites attach the star tracker directly to either the payload camera 'barrel' or to the same structure that the barrel is mounted to. This minimises the number of interfaces between the 2 entities, which removes the impact of thermo-elastic effects.
- Some payloads may have requirements not to point the payload at the sun for any period of time. It is key that these requirements are understood as they can impact the design of the AOCS especially when applied to safe mode activities.
- Furthermore, due to the high level of data generated in EO missions, a high data rate is required to downlink the captured images when in contact with a ground station. To achieve this high data rate using directional antennas, an EO satellite will most likely need to slew and track a ground station when conducting a downlink.

6.4 Power

- As mentioned in Section 4, EO payloads may be on either for targeted events and image captures, or more long term for strip mapping. Visible EO payloads will obviously be powered down during the eclipse period.
- The power system must therefore be sized to cope with 'large' peak demands when the payload is powered and when the payload downlink is active, especially if this is occurring during imaging, which can be the case. In addition, the payload requires mass memory storage for the data collected. This can either be volatile or non-volatile, and the choice is generally driven by the speed of the memory. If volatile data storage is used, this clearly has a constant underlying power that must be factored in.
- The batteries must also be sized appropriately by considering the maximum permissible depth of discharge (DoD) across the mission lifetime. The DoD value is limited by the number of charge/discharge cycles that the battery will have to complete which is of course a function of the length of the mission. The batteries must be large enough to power the spacecraft when in eclipse,

whilst not exceeding the maximum DoD value. LEO satellites experience a larger number of charge/discharge cycles due to regular eclipses. For example, 15 cycles a day for 5 years is 27,375. This means that the restriction on the permissible DoD is tighter than for spacecraft in MEO and GEO on which you may only have < 2000 cycles.

- The type and position of solar arrays needs to be able to provide sufficient power in both the nadir pointing cases, but also during any off-pointing events, such as imaging and downlinking. Deployable panels can be used, but these can create dynamics that have to be handled, especially if the satellite is agile. Where possible body mounted panels are preferred, unless this unduly effects the size of the satellite. The table below provides images showing the configuration of some EO satellites.
- The power of the payloads and payload transmitters can vary between a few watts to more than a 100 W for the larger satellites. The table below provides some examples of solar panel configurations on EO spacecraft.

Spacecraft and Solar Panel Configuration	Spacecraft and Image Source
	BlackSky-Global -5&6 [RD-11]
	Planet: Skysat Source: https://space.skyrocket.de/doc_sdat/skysat-3.htm
	Planet: Dove [RD-16]

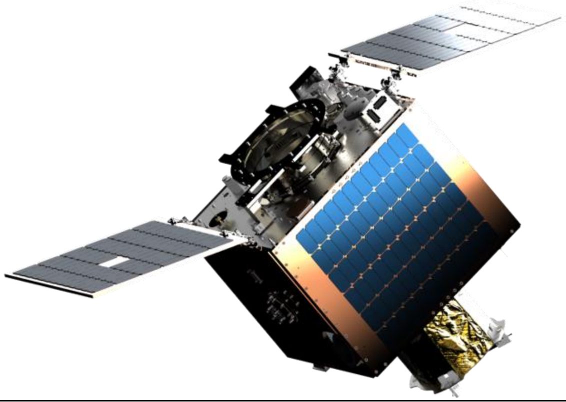
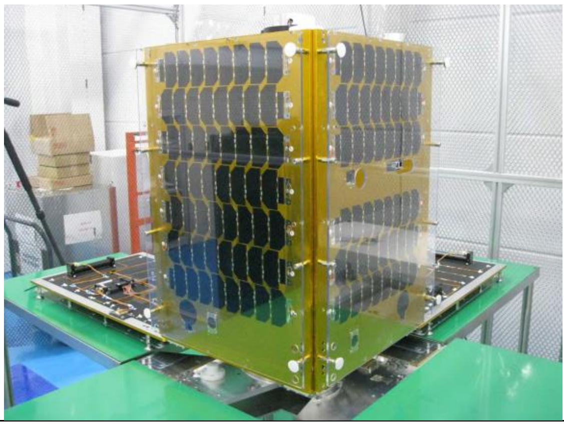
Spacecraft and Solar Panel Configuration	Spacecraft and Image Source
	Carbonite-2 Source: https://space.skyrocket.de/doc_sdat/carbonite-2.htm
	CE-SAT-1 Source: https://www.canonwatch.com/canons-satellite-ce-sat-1-is-in-orbit-building-a-high-resolution-earth-imaging-system-using-eos-5d-mark-iii/

Figure 6-1: Examples of EO satellites showing solar panel configurations.

6.5 Thermal

- The key thermal aspect with EO missions is to try and maintain a stable environment for the payload, such as minimising thermal gradients across the imaging barrel and keeping the temperatures along the barrel within the specifications of the payload. This is to ensure that the focusing and the positions of optics are kept stable to prevent degradation in the image.
- This can be achieved either by passive means using multi-layer insulation (MLI) and isolating interfaces or with the use of operational and survival heaters, or a combination of all three.

6.6 Structure

- The structure may vary from a few kgs for CubeSat payloads to 100 kg for larger satellites.
- Structures for EO missions tend to be based around 2 main configurations. The platform is either placed underneath the imager or around the imager. In some instances, it can be both.
- Figure 6-2 shows CE-SAT 1. The area under the primary mirror has some of the platform units, with the others on the panel that enclose the imager barrel.
- Figure 6-3 shows the layout of Planet’s Dove satellites which are an example of a structure with the platform underneath the imager.

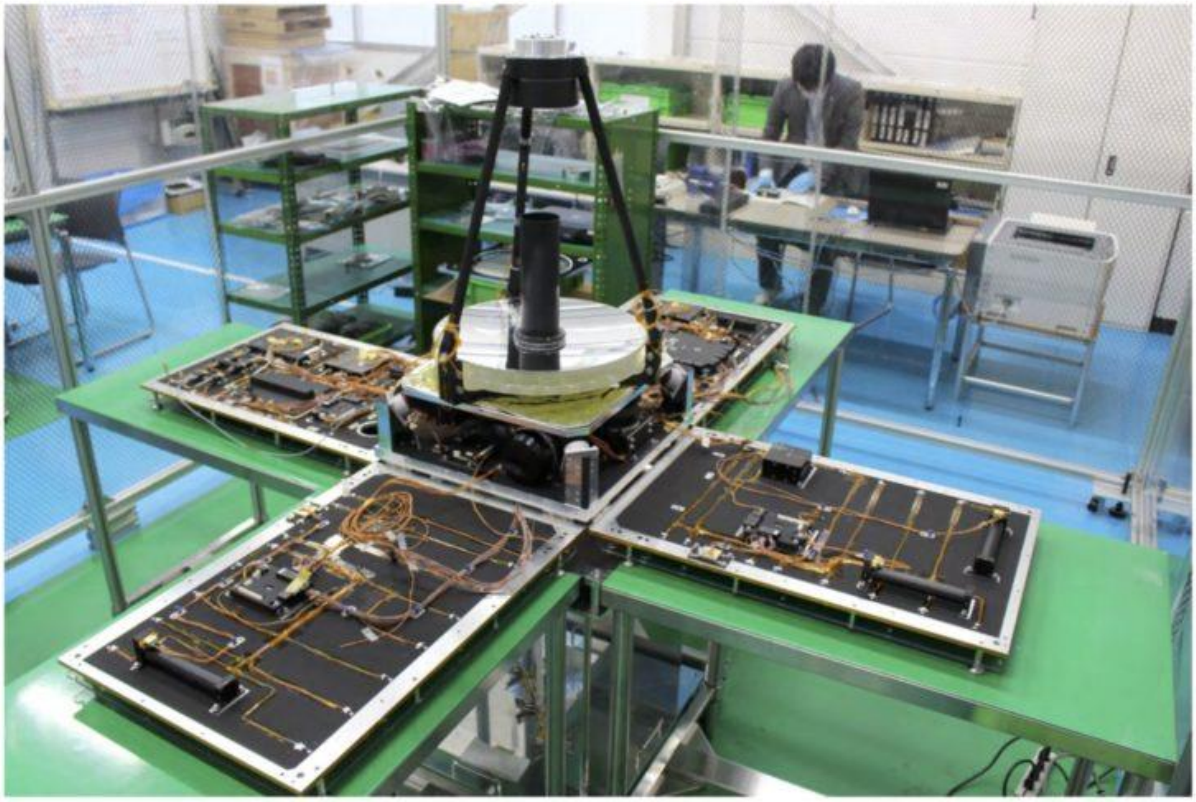


Figure 6-2: CE-SAT 1 partially assembled.

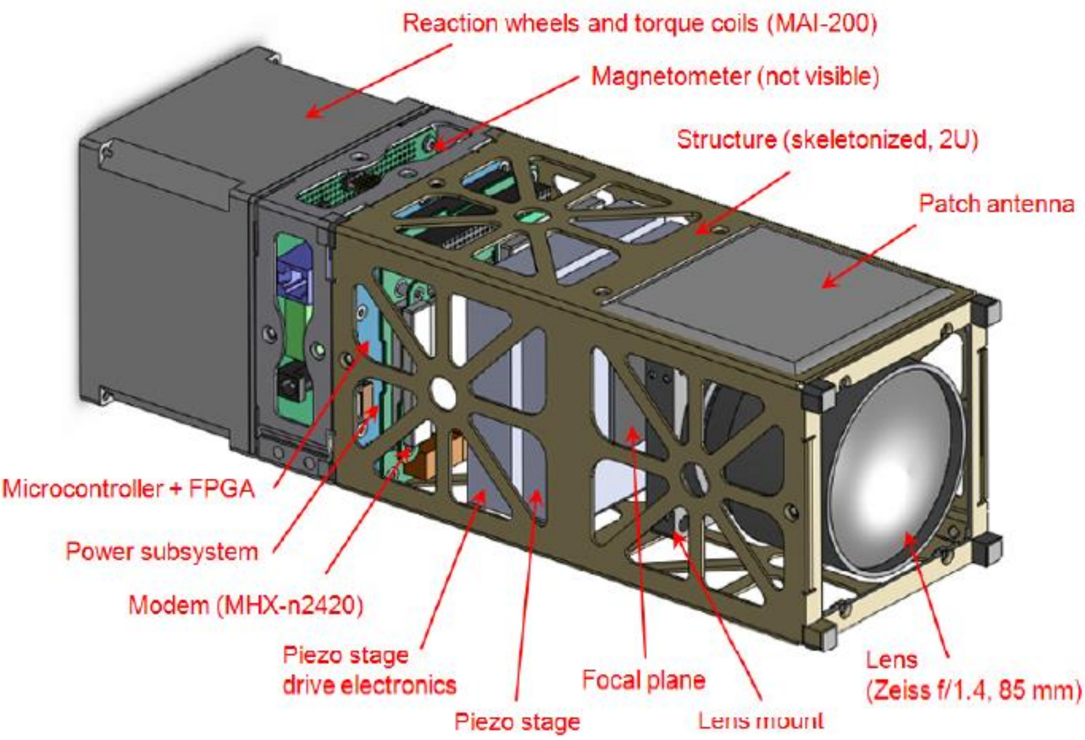


Figure 6-3: View of the units within the Planet Dove satellites [RD-12].

6.7 Propulsion

- To perform the task of imaging, EO satellites do not need propulsion. However, many carry propulsion in order to:
    - Get to an operational altitude
    - Phase with other satellites in the constellation. This is the key reason why EO satellites may require propulsion. However, early Planet Doves used to use their arrays to provide preferential drag to maintain phasing.
    - Collision avoidance
- Propellants used can be cold gas systems or green propellants such as High Performance Green Propellant (HPGP) (used on Skysat and provided by ECAPS [RD-13]) or water (used on BlackSky Global, [RD-11] [RD-14]).

7 Operations Overview

7.1 Introduction

- The operations of an EO satellite will depend on the type of satellite and the application that the data is being used to fulfil.
- Monitoring, as done by Planet with their Dove satellites [RD-17], has continuous imaging during the sunlit part of the orbit. Commanding is done over UHF from a small number of TT&C ground stations to command when the satellites image and downlink, with the data coming down via a distributed network of X-band ground stations before being forwarded to the storage and processing centre. The TT&C ground stations are also used for ranging for more accurate information on the orbital parameters. The satellites point nadir over land and image. When there is a ground contact the satellite tracks the ground station (currently they have 45 ground stations) under the satellite. During the rest of the time the satellites charge their batteries in a commanded background drag profile optimised for spacing the constellation over time. No real time commanding or 24/7 operations occur. Doves are all about generating a repository of data for people to then use.
- Tasking craft for specific images is generally the result of a mission planning system that has taken in requests from customers and then determined when that request can be met by a particular satellite. The time/location of the image/video or strip to be imaged is uploaded to the satellite via a TT&C ground station for execution in the future. The time between customer request, mission planning and image capture is variable depending on the location of the image, the number of satellites available to meet the request and the number of ground stations. However, for commercial satellites it is generally not real-time tasking. Once the satellite has taken the image, this will either be stored on board for later downloading, or will be sent directly to a ground station if one is in the same vicinity as the image capture (this is called near real time imaging and downlinking). The data can either be broadcast to a ground station (generally over X-band), which could be a customer owned one, without any uplink required (if parts of the image are lost then this will appear as blank areas of the image), or it can downloaded to a ground station with an uplink to allow any missing data to be re-requested. Once the data has been successfully received, the data on-board can either be deleted or overwritten with new data. Management of on-board storage can either be done from the ground or on-board.
- With more and more data being collected as resolutions become higher, data processing on board to reduce the burden on the downlink is becoming more common. This can be compression, either lossless or lossy, or processing of the image to determine if there is any data worth transmitting to the ground. For example, cloud detection can take place to determine if the image is cloudy. If it is, it can either be deleted, or marked for lower priority download.
- If low latency of data is required, the use of multiple data downlink ground stations is employed. For sun-synchronous orbits, high latitude ground stations are particularly useful, as the satellites see these every orbit. Currently EO satellites do not use inter-satellite links (ISLs) to improve latency.

7.2 Pre-launch

- For satellites that have propulsion, filling activities may need to be performed at the launch site. For CubeSats, this may already have been performed, depending on the propellant.
- Functional testing will be carried out to ensure that the satellite is fit for flight and then the satellite will either be attached to a separation system or loaded into a dispenser (if it is a CubeSat).
- Non-dispenser launched satellites may request trickle-charging of the battery whilst integrated to the rocket. This will depend on the length of time the satellite is integrated prior to launch and the allowable depth of discharge of the battery at launch.

7.3 Launch and Early Orbit Phase (LEOP)

- CubeSat EO satellites are powered off as they are launched from dispensers which keep the power system isolated. The majority of other micro-satellites are also powered off at launch through their separation systems.
- What happens immediately on separation from the launcher will depend on how passively safe the satellite is and how much autonomy is present. The simplest operational concept is to let the satellite tumble at the separation rate until the first link session is undertaken. Contact can then be established, and a health check of the satellite conducted before calibration of AOCS sensors and commencement of de-tumbling. Calibration of AOCS sensors can be performed on the ground prior to launch, or directly after launch either manually directed or autonomously. The quickest method of calibrating AOCS sensors would be to do so autonomously similar to the capabilities that Planet's Dove satellites have.
- The methodology depends on the size of satellite (it is easier for CubeSats to be calibrated on the ground), the level of complexity the project is comfortable with and the speed at which LEOP and commissioning needs to be performed.
- A lot of launches go to sun-synchronous orbits, and so it is normal for satellites to be dropped off close to their desired orbit, in terms of inclination. The exact operating altitude may not be possible especially due to rideshare, so it is possible that some form of propellant may be required, or a non-optimal orbit accepted in return for a timely launch.
- This is not the case for inclined orbits, which tend to be more bespoke launches.
- More EO constellations are being flown in order to provide faster revisit times over areas of interest. If these are launched on a single launcher, propulsion is generally needed to phase the satellites within the orbital plane.
- Planet have described what they do with their Dove satellites in RD-9. There is an initial contact with satellite over UHF to establish that the satellites are operational and with multiple 'pings' of the craft Planet can establish a rough orbit for the satellite. Once the health of the satellites has been autonomously checked out, through a review of battery charge, spin rates, temperatures and OBC health, the satellites enter pre-planned commissioning procedures. This covers detumbling and stabilisation (via magnetorquers and then wheels), solar panel deployment, and software upgrades (if applicable). Once this is complete Planet go into a period of platform sensor calibration, including magnetometers, gyros, sun and star trackers and the imaging telescope (to measure its position relative to the main AOCS sensors, see Geometric calibration below).

7.4 Payload commissioning

- The satellite has to be nadir pointing before payload commissioning can commence, as this generally requires imaging of key places on the Earth. General image taking to commission the functional payload chain can be performed by taking images of different types of terrain, such as cities, airports and other well known features. Such landscapes contain multiple straight lines which allow you to asses the impact of any wobble or jitter of the satellite on the quality of the images. Because of this, US cities work particularly well due to their block layout.
- For performance verification of SNR, MTF and stability the platform has to be fully commissioned to ensure that the AOCS is performing as it is expected to during the nominal mission. This is not only to stop inadvertent impact on the results, but also to ensure that the key targets, such as MTF sites and radiometric calibration sites can be targeted accurately to minimise commissioning time.
- The payload can be tested either as a complete chain by taking an image, or the pieces can be tested individually before the complete system is activated. The approach taken depends on the complexity of the payload, time constraints and risk profile of the mission. If the payload is reliant on a deployable or mechanically driven antenna, it is generally good to understand whether this is working correctly before trying to capture and download an image.
- The flow of activities for an EO payload can include:

  - General image capture to determine functional health
  - Calibration of AOCS pointing with respect to payload (Geometric calibration) for targeting missions
  - Radiometric calibration using test sites with calibrated/known radiance levels (such as Libya-4), white images using icesheets of Antarctica (Dome-C)/Greenland to relatively calibrate all pixels in the array and dark images over the Pacific to determine the dark noise of the detector. Other bodies such as the moon can be used for calibration, but this requires the system to be capable of pointing away from the Earth.
  - Signal-Noise Ratio (SNR) measurements – these can be tricky to perform in orbit and usually include taking images of homogenous targets such as snow or deserts. However, these only provide a single point measurement. Another way of determining the SNR can be to analysis normal images collected during imaging which will provide more information on the performance of the imager over the whole dynamic range.
  - Modular Transfer Function (MTF) measurements – this is a measure of the contrast that the imager can determine and an accurate figure for the in-orbit MTF of a system can be difficult to determine as it is impacted by not only the atmosphere but also the AOCS. Imaging of well-kept MTF sites (for example in China (Baotou), France (Salon de Provence), US (Stennis) [RD-18]) which provide patterns of black and white areas can be performed but may not be suitable for certain resolutions/swath widths. Analysis methods of these images can use either point source or knife-edge approaches. Comparison against other images and in-orbit systems can also be performed to provide a qualitative value.
  - Focusing – the level of focusing campaign is related to the resolution and complexity of the imager. Some more simple imagers have a fixed focus and therefore cannot be changed after launch. Others, especially higher resolution cameras have focussing mechanisms, that are used not only during the initial commissioning campaign, but also to take out effects of thermal season variation. A focussing campaign normally requires multiple images of targets with hard edges, such as MTF targets and cities.
- Which of the activities above are conducted depends on the application that the imagery is to be used for and the resolution and performance requirements.
- Calibration of the imagers happens at regular intervals through life to ensure any drifts or degradation is compensated for. The TripleSat imager was calibrated once a year during a calibration campaign, whereas Planet calibrate their imager autonomously every month [RD-4] [RD-12].
- Some EO satellites will also use the moon as a calibration source. This does however place an extra requirement on the AOCS as the satellite must then be capable of conducting such a pointing.

7.5 Nominal operations

- Payload Operations:
  - During the nominal lifetime of the satellite the payload operations are dictated by the application that the satellite has been designed to meet.
  - The payload operations tend to fall into 2 approaches:
    - Collecting data to generate a catalogue/repository of data that people can request
    - Targeted image capture requested by the user.
  - Taking the first approach, Planet Doves are designed to operate with the payload always on during sunlight. Data is then downloaded via a constellation of X-band ground stations, with each satellite sending its data down straight to the ground. This data is then processed and is ready for procurement. Landsat, also operates more in a 'monitoring' role, collecting large quantities of data, at relatively low resolution, but with the capability to perform special images for disaster monitoring.
  - Other EO satellites such as RapidEye, TripleSat and Kestrel Eye [RD-4] [RD-7] [RD-10] operate on a targeted basis. The customer/user will select a target for the satellite to image, which will then activate the payload at the correct point in the orbit, the image is taken, and then

the data is stored until it can be downloaded through a payload ground station. This target can either be a specific image or 'scene', or it can be a strip of ground, made of many scenes stitched together. The application determines what the 'target' will be.

- AOCS activities can be performed in parallel with configuring the payload with the correct imaging parameters such that when the image capture time occurs, the satellite and imager are ready. Some satellites will require additional platform units to be powered during imaging and these activities have to be timed with respect to the imaging starting.
- Exact timing needed for the image is calculated from the requested time and information provided from the GPS to calculate the specific time that the payload will be over the target.
- To ensure that the imager is thermally stable, and configured, this will also be turned on a few minutes prior to the image actually occurring. This is specific to the design of the imager and sensor.
- The number of payload files that are sent up per day depends on the configuration of the ground infrastructure, the mission planning system and the operational concept that is being employed. Generally, payload operations files are small files that can be uplinked with low rates, allowing UHF and S-band frequencies to be used.
- In order to ensure that the satellite is capable of performing all the operations requested by customers, they are modelled through a mission planning tool to determine the power required, whether the time between images is acceptable (for re-pointing and reconfiguration of the imager), memory usage and when the data will be downloaded. Customers are given a daily deadline by when their requests for images need to be provided and the length of time ahead of the event that they need to submit requests.
- Urgent requests for disaster monitoring can result in quicker responses depending on the area to be imaged and the time for the satellites to be over the required area.
- Payloads may have different modes that can be set, which tend to be related to what type and amount of imagery is required. For example, satellites may be able to take both long strip images and specific single scenes (such as UK-DMC-2). Other EO satellites have the capability to do area or stereo modes (such as NigeriaSat-2). These parameters are sent up in the payload file, together with parameters for controlling the set-up of the imager, such as exposure and integration time. For video imagery, the frame rate of the video can also be set [RD-4].
- Downloading of the imagery is also automated by the use of the payload command file to manipulate the data into the correct storage area at the correct time to be ready for downloading to the ground station. For higher rate X-band systems, either the platform has to point and track the ground station, or the X-band antennas are pointed to the ground station. If the EO satellite has the capability to compress and encrypt the payload data, then this will need to be done either prior to the start of the downlink, or in real-time as the data is streamed down. The time and place that this activity is done usually depends on the on-board payload processing capability.
- For satellites that collect large amounts of data, such as Planet, the payload command file may only provide simple stop/start times for entry into, and exit from, eclipse, together with any imager parameter setting and what type of compression.
- If a satellite is being used in a targeting mode, the imager is generally off until it is required to take a picture. Therefore, before any imaging can take place the imager needs to be turned on to 'warm up' and be configured. 'Warm up' time is required to ensure that the sensor is at a stable temperature so that the SNR will be consistent across the sensor.
- Generally, when a satellite is not imaging it will be kept in Nadir pointing mode with the minimum equipment powered. When an imaging event is due to occur, the EO satellite will need more accurate positional knowledge and attitude control. Therefore additional units such as GPS receivers, star trackers and gyroscopes may be activated to achieve the pointing accuracy required to image the target on the ground. Depending on the exact CONOPs of

the spacecraft however, some of these units may already be switched on. If the spacecraft needs to slew and point at the imaging target some time may need to be allocated before the image is taken for the satellite to stabilise to ensure it is accurately pointed at the target location.
    - After the image has been taken, the imager is powered down. This is usually a scheduled command based on the time of image capture and knowledge of how long the image will take to perform. The satellite transitions to nadir pointing and coarse pointing mode and the GPS is powered down.
    - The speed of off-pointing is generally dictated by the customer and it is a compromise between speed and size/power of wheels together with stability. Larger satellites have 2 sets of reaction wheels, smaller ones for controlling attitude and larger ones which are only on when the satellite is being manoeuvred. These wheels provide the fast slew capability, but have tended to have coarser speed control, and therefore produce more jitter if run whilst the satellite is imaging.
- Payload Pointing:
    - Nominally the payload will always be nadir pointing during this phase, although some payloads can use the moon as a calibration source.
    - Some payloads are more sensitive than others but generally it is not sensible to point the imager directly at the sun. Depending on the design of the imager, this can be accommodated for short periods of time, such as if the satellite is randomly tumbling, the sun travelling across the imager field of view is not an issue, as long as the time taken is not in the order of 10s of seconds. If the imager is pointed at the sun for long periods of time you can get hot spots on the detector which can damage it or the detector can be thermally shocked by heating it up too quickly. As there is a lens in front of the CCD the incoming light is focused and intensified. As this is a thermal issue it doesn't matter if the payload is on or off. This is a consideration to be taken into account when designing the mission safe mode.
- Inter-Satellite Communications:
    - Currently EO satellites do not use ISLs, with data being sent directly to ground stations. The approach for getting more data down, with lower latency appears to be to fly more satellites and have networks of ground stations to receive the data, whether this is larger fixed dishes, or mobile dishes for the people in the field. ISLs to transfer payload data could be quite difficult to implement as the need for high data rates would result in these being either Laser or X-band based, which would provide stringent point requirements on the bus, or the need for pointing systems, increasing complexity and mass.
    - ISLs for TT&C might be more plausible, for tasking of satellites that are not currently in visibility of the TT&C ground station but are closer to the target image. This would allow images to be taken with the most appropriate satellite to reduce the latency between request and delivery. This does put increased requirements on the mission planning aspects of the constellation. Having a low data rate would mean that radio frequency (RF) S-band or UHF ISLs could be used, with much wider beamwidths
    - There are 2 architectural options for the use of ISL – either up to a higher altitude data relay satellite, or across to another satellite(s) in the constellation that is closer to a ground station. Both RF and Laser ISLs are being considered but this may take some time to be included regularly in EO satellites.
- Orbital Manoeuvres:
    - For nominal payload operations, EO satellites do not need to conduct orbital manoeuvres, once they are in the correct operational orbit and if applicable, phased with other satellites in the constellation.
    - Mission orbital manoeuvres required are covered in sections below.
- Payload Deployables:

- Most EO payloads do not have any deployables or mechanisms. Some cameras may have a 'lens cap' that closes off the optics during launch (to protect against dirt falling on the optics during fairing enclosure and launch) and is then required to be opened once in-orbit. However, this does run the risk that this door cannot be opened, and the mission is lost. With certain satellites (E.g. Planet Doves, Skysat) the lens cap is combined with a deployable antenna, so that the action of opening the door also deploys the antenna [RD-3] [RD-5].

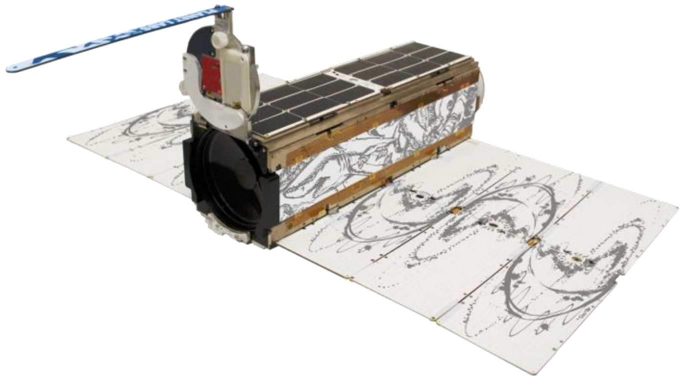


Figure 7-1: Imager lens cap and antenna deployment of Planet's Dove satellite [RD-3].

- Other deployables tend to be platform deployables to provide sufficient power for operations.
- Most deployables use either a non-explosive actuator (NEA) or a burn wire system. The latter can generally only be used with low mass deployables due to the strength of the wire.

- Payload Time Requirements:
  - The satellite will need to know the time accurately in order to schedule image captures, unless the tasking is performed using geolocation, i.e. the latitude/longitude of the image is provided and the satellite determines when the craft is in the correct location to take the image.
  - This is usually provided by a GPS receiver that synchronises the platform OBC. Time will need to be passed to the payload so that the data can be timestamped as it is collected for use in the ground processing. How this time is then passed to the payload will depend on the satellite and payload architecture/design.
  - A pulse-per-second (PPS) signal from the platform can be used to trigger image captures.
- Payload Attitude/orbit data:
  - The payload itself does not need attitude or orbit data to perform its image capture. However, ground processing will use attitude and orbit data to aid in the processing of the payload data. This data is normally sent down either appended to the payload data or as separate data files. If the former is done, the payload will need to have access to the attitude and orbit data to attach it to the imagery.

7.6 ICD Questions

- There is no such thing as a standard size of an EO payload as it depends on the GSD of the imager, along with other parameters such as SNR and MTF. These dictate the optical design and therefore the size of the primary mirror and the length of the telescope. Imagers can vary between 2m in length to a size that can fit in a 3U payload.
- Likewise, the power will vary dramatically depending on the imager electronics, the thermal design, the amount of data storage and the requirement of the transmitter.
- The imager requires a nadir facing field of view that is unobscured. A light shield can be used to minimise stray light coming in off other parts of the satellite.
- Data storage requirements for EO missions are increasing as higher resolution imagers are flown, and satellites are capable of taking more images. This also impacts the speed of download as well.

Satellites are now flying with 1 Terabyte drives to meet the demand. Data storage devices need to have high read/write capability at the same time as large storage volumes. Storage is also power hungry, so the ability to power down a device when not in use is a driver. These requirements can be in direct conflict, resulting in some missions having different types of storage for long and short term uses. This however can significantly complicate the operational planning. Rather than storing/downloading a lot of data, some satellites are looking into how payload processing can be used to only keep hold of 'useful' imagery and throw away data that is not viable, such as that ruined by cloud. This then results in increased processing requirements for the payload.

- For high resolution cameras, controlling the thermal conditions of the imager are important. Imager barrels can be made out of material that has limited thermal expansion, or consistent thermal expansion in all directions. Thermal gradients across and along the payload imager should be minimised.
- Maintaining the alignment between the star tracker(s) and the imager line of sight allows the ground processing to be able to geolocate the images using the same coefficients, rather than having to calculate the coefficients multiple times through the year. If it is not possible to do this, then regular calibration campaigns may be required. CCD and array sensors generate more dark noise the hotter they are, so maintaining the sensor at an ambient temperature is sensible.
- Imaging payloads need to be held steady otherwise the resultant image can look blurred, or straight lines can appear wobbly. This can be the result of either:
    - micro-vibration: small high-frequency, low energy vibrations generated by mechanisms such as wheels or antenna pointing mechanisms (APMs) that excite the satellites structural modes
    - jitter: line of sight instability or high frequency platform oscillation higher than the satellite attitude controller bandwidth which is therefore not compensated/controlled by the satellite attitude control system
    - longer-term AOCS stability issues.
- Micro-vibration can either be dealt with by ensuring that any mechanisms on board the satellite do not generate energy that can stimulate modes or by isolating the imager from the noise. The latter has an impact on how the imager is mounted within the structure. Controlling jitter depends on control loop speeds with respect to the noise generated, and feeds into the design of the AOCS system, both from the software and the component selection.

7.7 Non-routine Operations

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

For EO missions, non-routine operations can include:

- Regular calibration and focusing campaigns for determining status/change in imager configuration parameters:
    - Seasonal orbital and thermal effects can change the focussing of an imager which needs to be updated. Calibration campaigns tend to be run yearly to understand the performance of the sensor and how it has degraded over the year. This might require changes to drive voltages or integration times to increase the signal levels seen. This may be controlled in a configuration file, depending on the design of the payload.
    - Calibration usually involves image captures of particular targets on the Earth, such as white/dark images (snow/Pacific at night), MTF targets, deserts, and urban/airport areas. In some cases the calibration may use the moon or dark sky. This would require a specific attitude mode to point away from the Earth.
- Orbital and/or phasing manoeuvres:

- Over life the orbit that the satellite is in will drift and this will affect the LTAN of the orbit and therefore the lighting conditions. If the initial orbit is selected carefully then the change in LTAN may be naturally controlled within the required range. If this is not possible, manoeuvres may be required to keep the LTAN value within a designated range.
  - If the satellite is part of a constellation, then phasing manoeuvres may be required to maintain phasing between the satellites. This may just be an altitude change, or an altitude and inclination change combined.
- Uploading new software
  - New software may be required if there are issues controlling the payload, or if failures/anomalies need to be worked around. There is nothing in the EO mission application that specifically requires software updates.
- Critical commanding
  - The deployment of the lens cap/antenna could be a command that needs to be specially authorised by the operator.
- Collision avoidance
  - This is becoming increasingly required, especially in key orbits such as sun-synchronous at altitudes from 500 to 680km.
- End-of-mission activities

7.8 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.

Sun in Field-of-view (FOV):

- As mentioned in Section 7.5 some imagers must not be pointed at the sun for extended periods of time. The grey area comes when the tumble rates are considered low prior to switching in a controlled attitude. The payload should be encouraged to be able to withstand the possibility of the sun tracking across the imager FOV at the slowest tumble rate that might occur.

Emergency power down sequence:

- If there is an issue with the satellite that requires the payload be quickly switched off whilst it is operating, it makes sense to utilise the same power down sequence as for nominal operations for the imager and its associated data storage. If operating, the payload downlink can be stopped immediately as this shouldn't affect the storage of data. Ancillary units such as GPS and star trackers will be controlled by the platform reconfiguration and can be done so independently of the payload.

Re-starting operations after an anomaly:

- If the payload has not caused the initial anomaly, then no additional care needs to be taken with it before re-starting operations. It is suggested that the status of the payload data stored should be examined, to understand what was saved during the shut-down so that downloads can be re-started successfully.

- If the payload was the cause of the anomaly, then a full investigation of the anomaly should be carried out. This should cover how to determine what the anomaly was and how the payload can be checked out safely prior to bringing it back into service.

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 considered that the payload would require additional FDIR than that specified above.

- Temperatures, currents, and certain imager parameters may be limit checked and then action taken if these are exceeded.

9 End-of-life operations

If an EO 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.

The payload itself does not need to be passivated prior to end-of-life. The operation required is to just turn the payload off. Deletion of data could be undertaken but is not essential.

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