CUBESPACE

CubeADCS Gen 2

Product Description

DOCUMENT NUMBER	CS-DEV.PD.CA-01
VERSION	1.03
DATE	30/10/2023
PREPARED BY	C. LEIBBRANDT, H. STEYN, L. VISAGIE
REVIEWED BY	HS, LV, FL, AS, DS
APPROVED BY	F. Louw
DISTRIBUTION LIST	External

Revision History

VERSION	AUTHORS	DATE	DESCRIPTION
1.00	C. Leibbrandt	06/12/2022	First formal release
1.01	C. Leibbrandt	11/04/2023	Updated to new CubeSpace branding
1.02	C. Leibbrandt	18/10/2023	Changed title of reference document [3] from “ADCS HW config and options” to “Client Mission Overview”
1.03	C. Leibbrandt	30/10/2023	Reference documents corrected

Reference Documents

The following documents are referenced in this document.

[1] CS-DEV.ICD.CA-01 CubeADCS standard ICD Ver.1.01 or later

[2] CS-DEV.GD.TPL-02 Client Mission Overview Ver.1.05 or later

List of Acronyms/Abbreviations

ACP	ADCS Control Program
ADCS	Attitude Determination and Control System
CAN	Controller Area Network
COTS	Commercial Off The Shelf
CSS	Coarse Sun Sensor
CVCM	Collected Volatile Condensable Materials
DUT	Device Under Test
EDAC	Error Detection and Correction
EHS	Earth Horizon Sensor
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
FDIR	Fault Detection, Isolation, and Recovery
FM	Flight Model
FSS	Fine Sun Sensor
GID	Global Identification
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GYR	Gyroscope
I2C	Inter-Integrated Circuit
ID	Identification
LTDN	Local Time of Descending Node
LEO	Low Earth Orbit
MCU	Microcontroller Unit
MEMS	Microelectromechanical System
MTM	Magnetometer
MTQ	Magnetorquer
NDA	Non-Disclosure Agreement
OBC	On-board Computer
PCB	Printed Circuit Board
RTC	Real-Time Clock
RWA	Reaction Wheel Assembly

RW	Reaction Wheel
SBC	Satellite Body Coordinate
SOFIA	Software Framework for Integrated ADCS
SPI	Serial Peripheral Interface
SRAM	Static Random-Access Memory
SSP	Sub-Satellite Point
STR	Star Tracker
TC	Telecommand
TCTLM	Telecommand and Telemetry (protocol)
TID	Total Ionizing Dose
TLM	Telemetry
TML	Total Mass Loss
UART	Universal Asynchronous Receiver/Transmitter

Table of Contents

Table of Tables

Table of Figures

1. Introduction

This document introduces the standard CubeSpace Attitude Determination and Control System (CubeADCS). The system and sub-systems are presented and described. The different configurations of the CubeADCS are introduced and guidance is provided to allow the reader to identify a potential system configuration that will satisfy their needs.

This document is a prelude to the standard CubeADCS ICD and standard CubeADCS User manual.

This standard CubeADCS product description henceforth lists all standard features, - characteristics and - capabilities in a summary form as an initial introduction to the product.

Different client scenarios are catered for, namely:

1. Purchasing of a standard CubeADCS offering by a knowledgeable client who requires no further assistance,
2. Purchasing of a CubeADCS where the client initially requires CubeSpace consultation and suggestions to be able to formulate a system configuration to serve as a solution for the client's needs,
3. Purchasing of a custom CubeADCS configuration to meet client's unique needs.

   Note: Realising that client requirements and -satellite missions may not necessarily be fulfilled by CubeSpace's standard CubeADCS offering as-is (as documented in the above-mentioned standard documents), custom orders are also catered for. From a documentation point of view, for such custom order situations, CubeSpace provides an additional "Client specific CubeADCS Addendum" document. This addendum document addresses all customization for that client.

2. Overview

The CubeADCS is made up of several sub-systems, also referred to as CubeProducts.

CubeADCS is designed with modularity in mind. Most of the devices are common across CubeProducts and are typically mass manufactured, resulting in short production times and increased reliability through repeatability.

The CubeADCS consists of an ADCS computer (the CubeComputer subsystem) and various other subsystem -sensors and -actuators, also referred to as nodes, connected via harnesses.

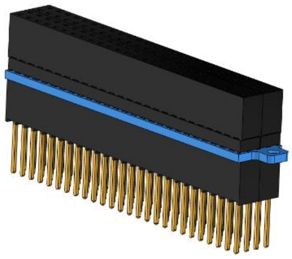
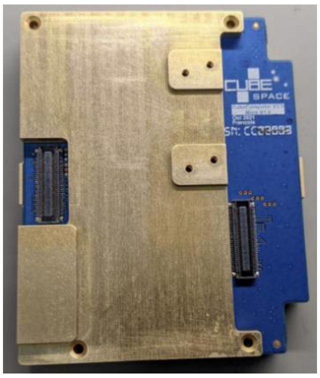
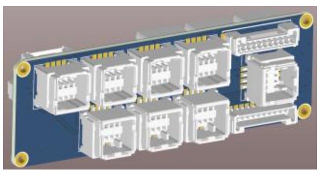
A flexible *core stack*, which includes at least the ADCS computer, in some cases potentially custom interfaces, and several ADCS nodes, is at the heart of CubeADCS. The nodes included in the *core stack* will depend on the specific use case (see Section 2.5 for examples).

The CubeADCS *core* includes the necessary elements (CubeDoor and CubeConnect) to interface with nodes that make up the ADCS solution and also externally with the host system (such as the satellite OBC).

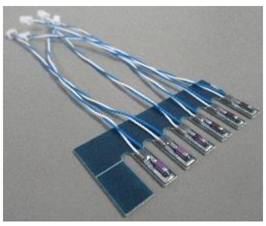
2.1.CubeProducts

The various items that can be included in a CubeADCS are described in Table 1.

Table 1: The sub-systems and CubeProducts of CubeADCS

Item	Description	
CubeDoor (Element of CubeADCS core) 	Description	Satellite Interface
	Details	Interface to client Satellite OBC. Standard PC104 version shown.
	Inclusion	Always included in CubeADCS and part of CubeADCS Core
	Quantity	1
	Generic Term	N/A
	CS Name and acronym	CubeDoor (CDo)
CubeComputer (Sub-System of CubeADCS core) 	Description	ADCS computer
	Details	• Runs all ADCS software, • Commands and controls all nodes
	Inclusion	Always included in CubeADCS solution and part of CubeADCS Core
	Quantity	1
	Generic term	ADCS OBC
	CS Name and acronym	CubeComputer (CC)
CubeConnect (Element of CubeADCS core) 	Description	Interface to nodes
	Details	Internal interface to CubeADCS nodes
	Inclusion	Always included in CubeADCS and part of the CubeADCS Core
	Quantity	1
	Generic Term	N/A
	CS Name and acronym	CubeConnect (CN)
CubeTorquer (Component of CubeADCS core) 	Description	Magnetic torque rod
	Details	• Ultra-low remanence magnetic actuators, • Available in various sizes from 0.2 Am^2 [CR0002] to 2.0 Am^2 [CR0020]
	Inclusion	Always included in CubeADCS
	Quantity	3
	Generic Term	Magnetorquer (MTQ)
	CS Name and acronym	CubeTorquer (CR)
CubeWheel (Sub-System)	Description	Balanced reaction- or momentum wheel
	Details	Accurately balanced by hand,

Item	Description	
		Excellent zero-crossing behaviour, Available in various sizes (CW0017, CW0057 and CW0162) to suit a wide range of missions
	Inclusion	Optional
	Quantity	Up to 4
	Generic Term	Reaction Wheel (RWL)
	CS Name and acronym	CubeWheel (CW)
CubeWheel Pyramid (Sub-System) 	Description	4 Wheels mounted in pyramid structure
	Details	Mounts all four wheels at optimal angles for redundancy
	Inclusion	Optional
	Quantity	1
	Generic Term	N/A
	CS Name and acronym	CubeWheel Pyramid (CW pyramid)
CubeMag Deployable (Sub-System) 	Description	Deployable magnetometer
	Details	• Very low sensitivity to temperature change, • Second (redundant) sensor included by default, • Deployment mechanism can be re-armed/re-stowed
	Inclusion	Always included in CubeADCS
	Quantity	1
	Generic Term	Deployable Magnetometer (MTM)
	CS Name and acronym	CubeMag (CM)
CubeMag Compact (Sub-System) 	Description	Compact redundant magnetometer
	Details	Compact magnetometer to complement primary CubeMag Deployable
	Inclusion	Optional
	Quantity	1
	Generic Term	Magnetometer (MTM)
	CS Name and acronym	CubeMag Compact (CMC)
CubeSense Sun (Sub-System) 	Description	CMOS-based fine sun sensor
	Details	• Fisheye lens with wide FoV, • Immune to earth and moon disturbances, • Superior accuracy versus photodiode-based sun sensor
	Inclusion	Optional
	Quantity	Up to 4
	Generic Term	Fine Sun Sensor (FSS)
	CS Name and acronym	CubeSense (CS)
CubeSense Earth (Sub-System)	Description	Infrared earth horizon sensor

Item	Description	
	Details	• Provides measurements in sunlight and eclipse, • Hermetically sealed lens, • Tolerates typical off-nadir angles
	Inclusion	Optional
	Quantity	Up to 2
	Generic Term	Earth Horizon Sensor (EHS)
	CS Name and acronym	CubeIR (CI)
CubeStar (Sub-System) 	Description	Low-power star tracker
	Details	• Lost in space and tracking modes • Baffle can easily be added (optional)
	Inclusion	Optional
	Quantity	Up to 2
	Generic Term	Star Tracker (STR)
	CS Name and acronym	CubeStar (CT)
Coarse Sun Sensors (Sub-System) 	Description	One-dimensional coarse sun sensors
	Details	• Photodiode array used to construct coarse sun vector, • Split into two groups of 5 sensors each
	Inclusion	Optional
	Quantity	10
	Generic Term	Coarse Sun Sensor (CSS)
	CS Name and acronym	Coarse Sun Sensor (CSS)
CubeNode (Sub-Systems) 	Description	Configurable interface for third party hardware
	Details	• Interfaces with third party hardware, • Eliminates the need for hardware changes on ADCS computer to accommodate third party hardware
	Inclusion	Optional
	Quantity	Up to 2
	Generic Term	N/A
	CS Name and acronym	CubeNode (CNo)

2.1.1. CubeADCS nomenclature

This subsection briefly defines CubeADCS related nomenclature/terms as used throughout CubeADCS documentation.

1.1.1.1 CubeADCS Core

The term "CubeADCS Core" is used to refer to the CubeComputer + CubeDoor + CubeConnect. The "CubeADCS Core" is fitted inside a standard mechanical housing / enclosure which may be customised if required. As the term implies, these three items, when combined serves as the core of all CubeADCS bundles.

All ADCS sensors and all ADCS actuators are mounted external to it.

It is shown diagrammatically in Figure 1 and pictorially in Figure 2 below.

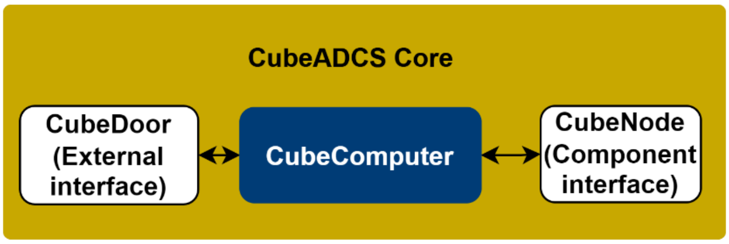


Figure 1: CubeADCS Core diagrammatic representation

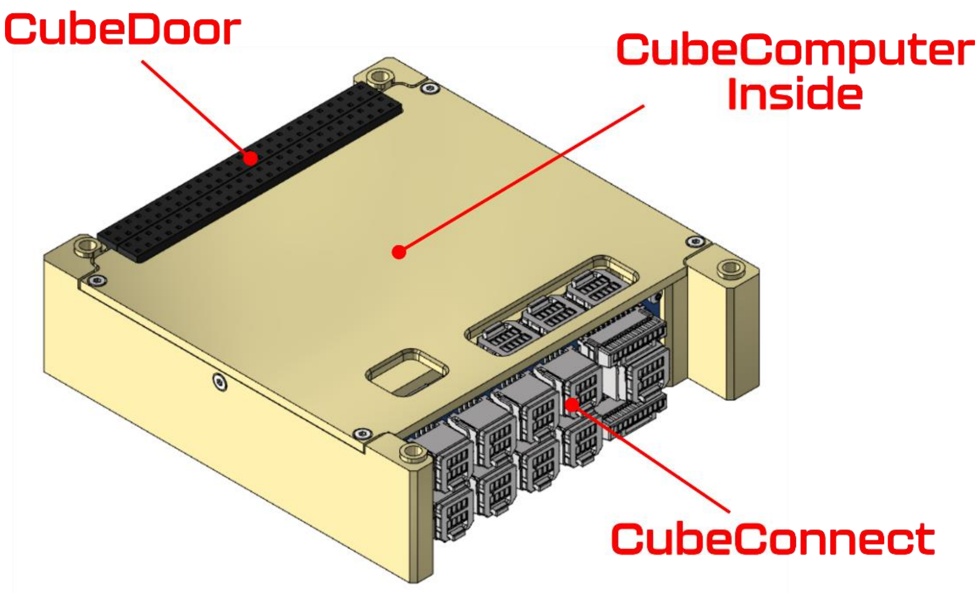


Figure 2: CubeADCS Core pictorial representation

1.1.1.2 CubeADCS Core Stack

The term "CubeADCS Core Stack" is used to refer to the CubeADCS Core (i.e. the CubeComputer + CubeDoor + CubeConnect) plus actuators all integrated and fitted inside a mechanical housing/enclosure. The CubeADCS Core Stack is supplied in two standard variants namely the

1. CubeADCS Core Stack for use in 3U satellites, and the
2. CubeADCS Core Stack for use in 6U satellites

The two variants include reaction wheels plus torquer rods suitably sized for the target satellite and the standard mechanical housing/enclosures are then sized to accommodate the actuators within a minimal total volume. Customisation of the standard housing/enclosures can be included if required.

Sensors are mounted externally to the CubeADCS Core Stack, suitably mounted on the satellite to maximise sensor fields of view (for optronic sensors) and to minimise magnetic field distortions for magnetometers.

It is shown diagrammatically in Figure 3 and pictorially in Figure 4 below.

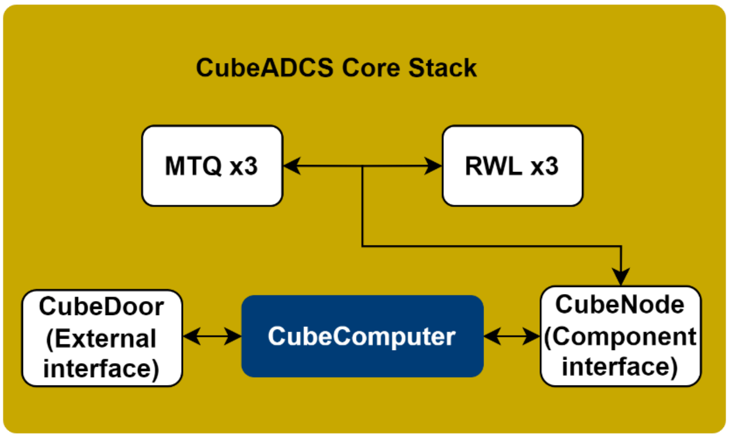


Figure 3: CubeADCS Core Stack diagrammatic representation

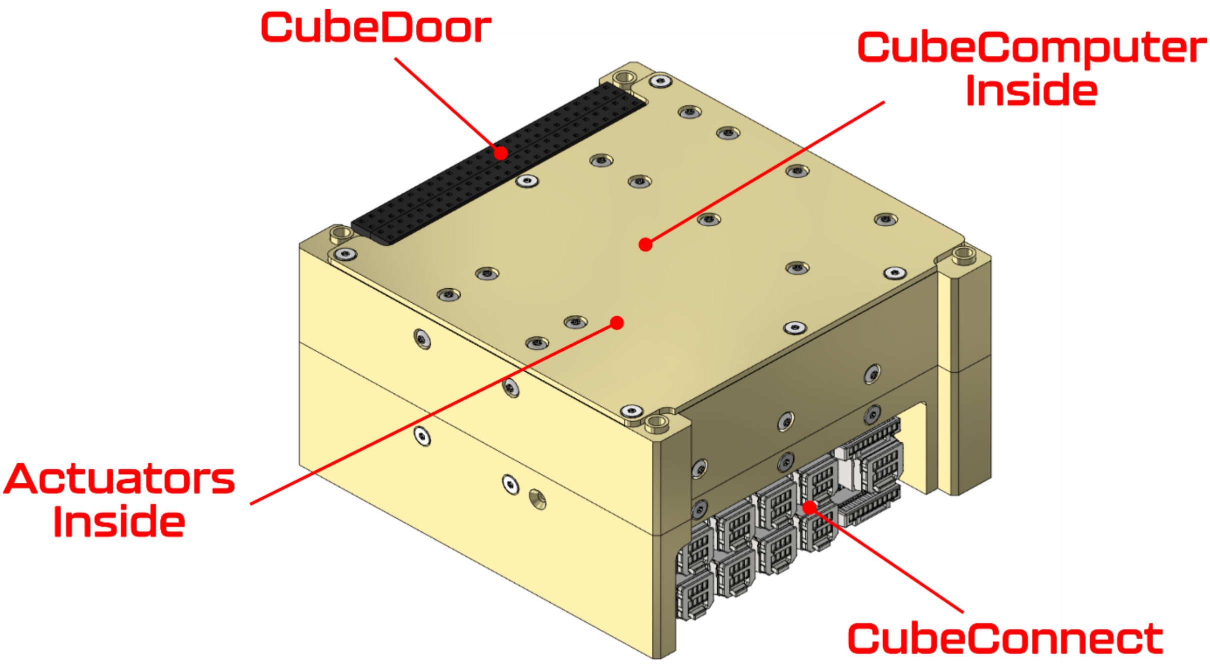


Figure 4: CubeADCS Core Stack pictorial representation

Sensors could be mounted inside the CubeADCS core stack if there is a specific client need for doing so, but this will be considered a custom order.

1.1.1.3 CubeADCS bundle

The term "CubeADCS bundle" is used to simply refer to everything that is included for a particular CubeADCS solution. It therefore includes all sensors, actuators, nodes, processing harnesses and mechanical mountings / housings.

2.1.2. Third Party sensors and actuators

The CubeADCS can also support certain third-party sensors and actuators with an initial list provided in Table 2. This is made possible via the CubeNode (see Table 1).

Table 2: CubeNode supported 3rd party Sensors and Actuators

3RD PARTY SENSORS AND ACTUATORS	DESCRIPTION	
Pico Star Tracker PST3S 	Description	Pico Star Tracker
	Details	Higher accuracy star tracker than CubeStar
	Inclusion	Optional
	Quantity	Up to 2
	Generic Term	Star Tracker
	Link	TY-Space

In addition, CubeADCS can interface to other external / third-party equipment, with an initial list provided in Table 3. This is made possible via the CubeDoor (see Table 1) in its standard form (i.e. not customised version).

Table 3: CubeDoor supported external / certain third-party equipment (initial list).

EXTERNAL / 3RD PARTY EQUIPMENT	DESCRIPTION	
SkyTraQ GNSS receiver (Supported model number S1216)	Description	GNSS Receiver for accurate position and velocity measurements
	Details	GNSS measurements are used for increased positional accuracy – for high-performance pointing requirements
	Inclusion	Optional
	Quantity	1
	Generic Term	GPS
	Link	SkyTraQ
u-Blox GNSS receiver (Supported model number ZED-f9P)	Description	GNSS Receiver for accurate position and velocity measurements
	Details	GNSS measurements are used for increased positional accuracy – for high-performance pointing requirements
	Inclusion	Optional
	Quantity	1
	Generic Term	GPS
	Link	u-blox

2.2.System diagram

Figure 5 provides a typical high-level system diagram of a CubeADCS.

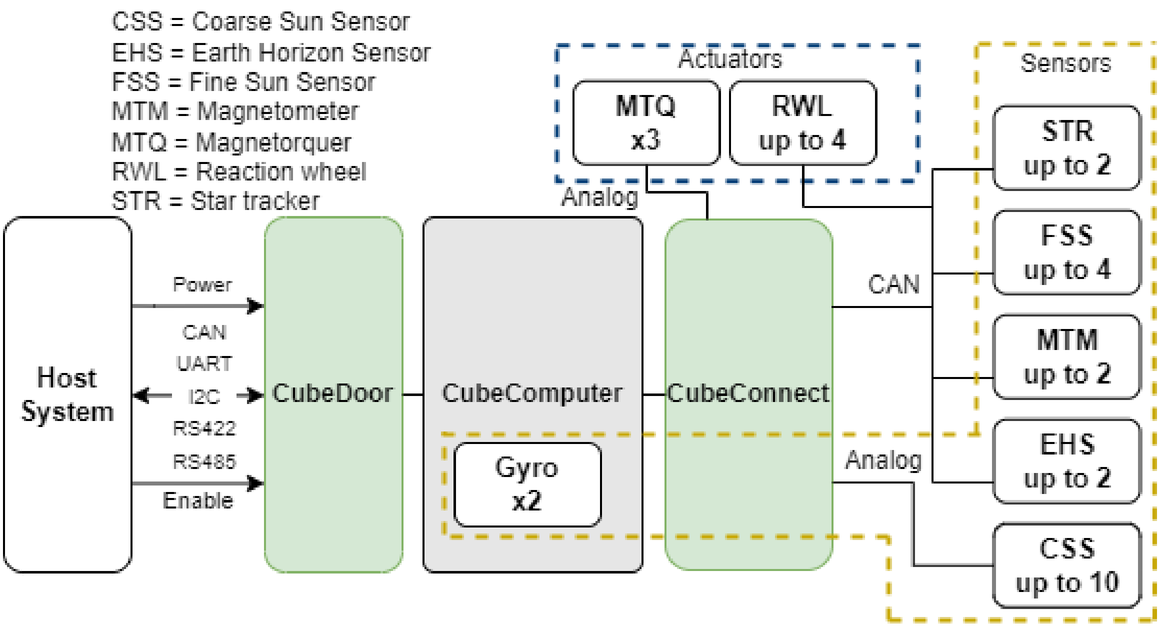


Figure 5: Typical high-level system diagram of CubeADCS

2.3.CubeADCS configurations

The CubeADCS is available in three general configurations, depending on the size of the satellite (more specifically, the required size of the actuators). The sub-systems of CubeADCS can be placed internally or externally to the core stack, as mentioned in section 2.1.1, depending on mission needs.

2.3.1. Integrated CubeADCS for 3U satellites and smaller

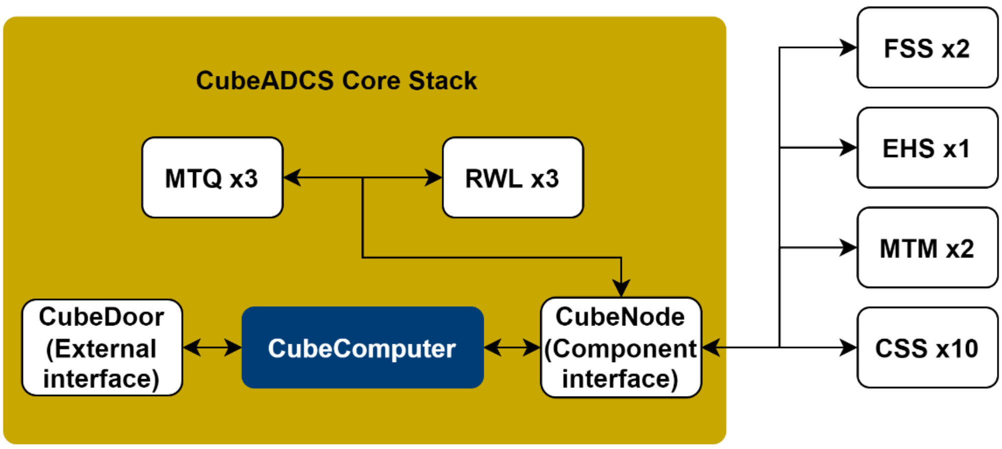


Figure 6: Integrated CubeADCS configuration: example for 3U and smaller satellites

Refer to Figure 4 for a pictorial representation of a Standard CubeADCS Core Stack for a 3U satellite.

2.3.2. Integrated CubeADCS for up to 6U satellites

Reaction wheels and magnetorquers are sized for satellites up to 6U (typically) and are integrated in the CubeADCS core stack (up to 3 wheels in orthogonal configuration). Figure 7 shows example block diagram of such a CubeADCS solution. Sensors are typically mounted externally, but custom integration into the core stack of some sensors could be accommodated (see [2]) depending on mission needs.

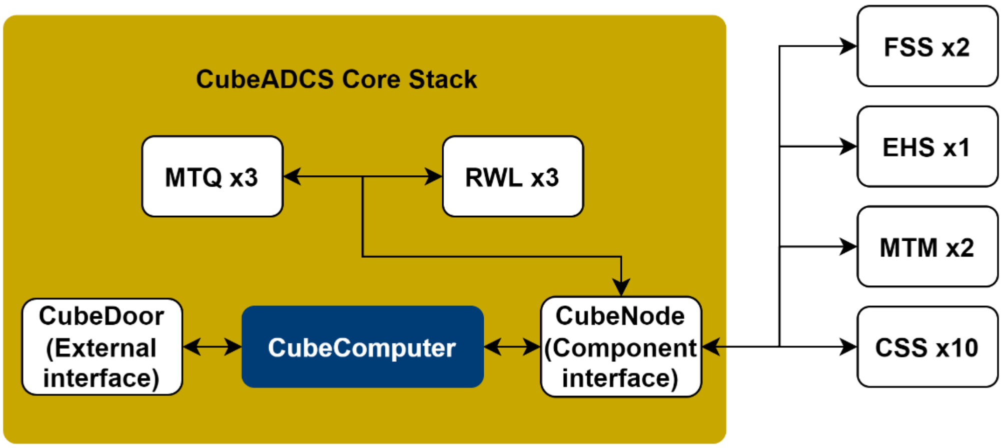


Figure 7: Integrated CubeADCS configuration: example for satellites up to 6U

Note: The above diagrammatic representation is "identical" to the one shown in Figure 6, with the difference only in terms of physical sizing of the actuators needed for the larger (6U) satellites. This physical difference in actuator sizing become evident in Figure 8 where-in the elongated dimension in the pictures "Z-axis" is longer / higher than the Standard CubeADCS Core Stack for a 3U satellite

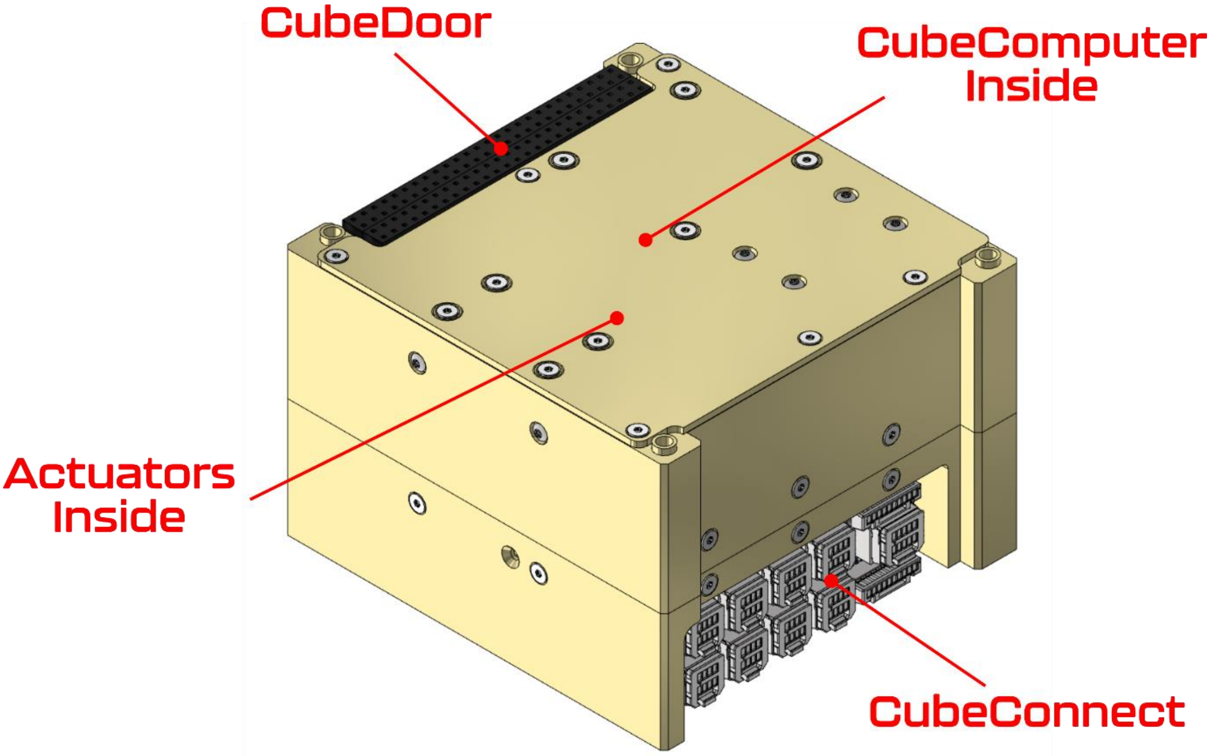


Figure 8: Standard CubeADCS Core Stack for a 6U satellite

2.3.3. Modular CubeADCS

A modular CubeADCS configuration is possible allowing for a custom layout of actuators and sensors for 6U satellites and larger. In this case, the CubeADCS core (refer section 2.1.1) and its standard enclosure is optimal while reaction wheels and magnetorquers are mounted externally to it, optimally within the satellite. The reaction wheels and magnetorquers can be easily scaled depending on mission requirements. In this configuration up to four wheels can be supported in a pyramid configuration. Sensors are also typically mounted externally to the CubeADCS Core. Figure 9 shows an example block diagram of such a CubeADCS solution.

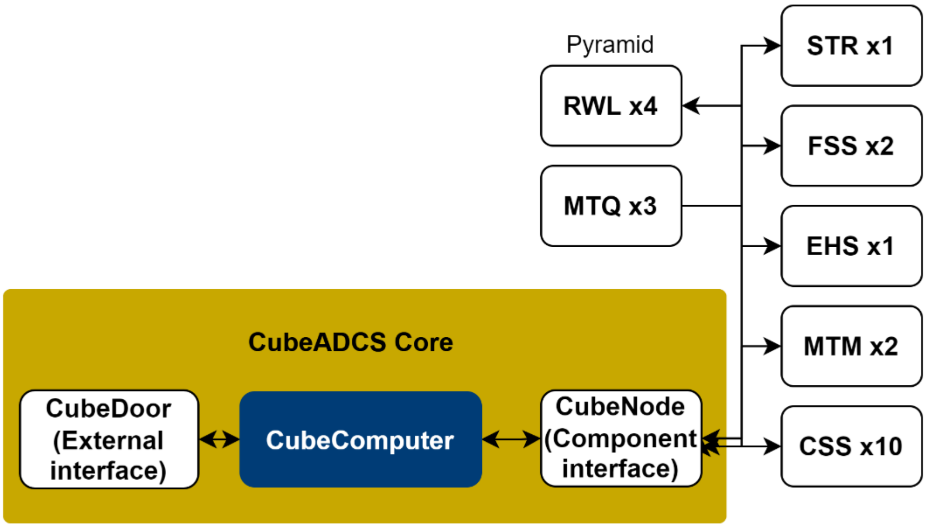


Figure 9: Modular CubeADCS configuration: Example

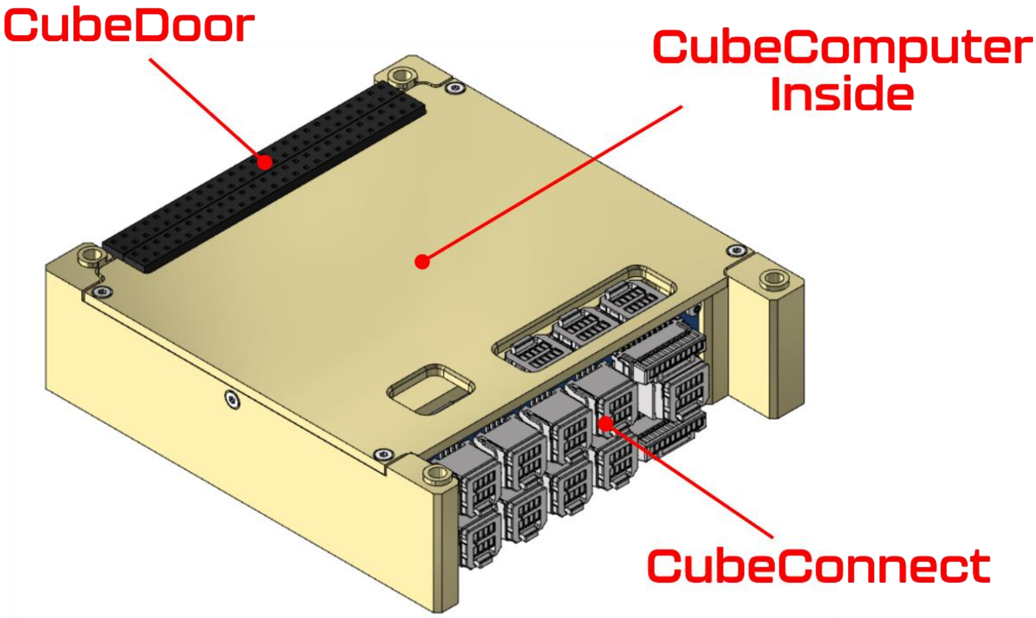


Figure 10: Standard CubeADCS Core

2.4.Interconnect of sensors and actuators

The various sensors and actuators are connected to the CubeADCS Core by means of harnesses. These harnesses are based on the Molex Micro-Lock Plus family of wire-to-board connectors. These harnesses are made using wires with low-outgassing insulation.

Note that the black wires available as off the shelf cable assemblies from some other vendors are made from PVC and do not have low outgassing properties.

All interface related information is detailed in the Standard CubeADCS Interface Control Document (ICD). Refer to [1].

2.5. Pre-loaded firmware applications

The CubeADCS is supplied with two pre-loaded applications on the unit. The first is a Bootloader and the other the Control Program.

2.5.1. Bootloader

The Bootloader is the first application to run when the CubeADCS is powered on. It has the following features:

- Loads and checks CubeADCS configurations,
- Auto discovery of nodes connected to CubeADCS,
- Allows Control Program and configuration to be updated,
- Allows Bootloader itself to be updated,
- Performs FDIR,
- Performs Event logging,
- Provides file- and log upload and download capability, and
- Exposes Bootloader API to Host Device over communication channels.

2.5.2. Control Program

The control program is the main program of the CubeADCS and performs the core attitude determination (estimation) and control functions. Some of the main functions are:

- Performing FDIR,
- Performing local event and TLM logging,
- File management,
- Managing all sub-systems (nodes) (e.g. power, status, setup, and configuration),
- Samples sensors,
- Runs ADCS estimation and control algorithms,
- Commands actuators,
- Exposes Control Program API to host device, and
- Automates ADCS mode switching and recovery, if enabled.

2.6. Support software (CubeSupport application)

The user is also provided with ground support software called CubeSupport. This allows the user to directly connect to the CubeADCS and to gain access to all telemetry values and all commands. The CubeSupport application also has convenient HMI elements for uploading- and upgrading firmware, and downloading event, image, and telemetry logs.

2.7. Simulation software (EOS): CubeSpace plugin

CubeSpace provides an optional plugin to an EOS satellite simulator. The CubeSpace ADCS plugin contains high-fidelity reference implementations of the CubeADCS algorithms which allows users to simulate and observe satellite responses under the various estimation- and control modes. The CubeSpace plugin together with the EOS simulator can be used to verify required ADCS performance, perform Processor-In-the-Loop (PIL) simulations, and estimate power consumption of the CubeADCS under various modes.

2.8. Support hardware (CubeSupport PCB)

CubeSpace provides ground support equipment to allow the user to power and interface with the CubeADCS out of the box. All required cables, interfaces and documentation is provided to allow the user to perform a health check of the CubeADCS upon delivery to the client.

2.9.Documentation

The CubeADCS is provided with a set of standard documents which are listed in Table 4:

Table 4: CubeADCS standard documentation

DOCUMENT	DESCRIPTION
Standard Product Description (PD) - (This Document)	Provides and overview of the standard CubeSpace CubeADCS offering. It is typically supplied to prospective clients to allow a better understanding of the CubeSpace CubeADCS offering
Standard Interface Control Document (ICD)	Detailed information about the physical aspects of the standard CubeADCS offering addressing technical aspects of all interfaces. It is typically supplied to prospective clients to allow a better understanding of the CubeSpace CubeADCS offering and in particular how to interface to it; electrically, mechanically and electronically
Hardware Configuration and Mission Overview	This is a form for a prospective client to complete. It lists all the available options for the CubeADCS. It assumes the user has already read the Product Description and the ICD. The prospective client can then make use of this document to provide CubeSpace with the important details about the user's mission which will affect the CubeADCS. The user can also indicate other needs and what optional features they would like to have with the CubeADCS.
API/NodeDef/XML	Describes the communication messages that the OBC will use to interface with the CubeADCS in detail. It is typically only supplied to actual clients.
Standard User Manual	Describes all functions and features in more detail (than provided in the Product Description). It also allows the user to conduct a Health Check to confirm the CubeADCS is "alive and well" after receipt of the shipment at the client. It is typically only supplied to actual clients.
Standard Commissioning Manual	Describes recommended commissioning steps It is typically only supplied to actual clients.
Client Specific Addendum	The Addendum documents all details of custom work (i.e. work that differs from the standard CubeADCS as documented in the standard CubeADCS documentation). It is only made available for a non-standard CubeADCS client order.
Software Guide	Describes how to make use of provided software packages It is typically only supplied to actual clients.
Common Firmware Reference Manual	Provides a complete description of protocols used by communication transport layers It is typically only supplied to actual clients.
Bootloader Application Note	Describes how to use the Bootloader and make use of all features It is typically only supplied to actual clients.
Declared Material List (DML)	This is an optional document and it is typically only supplied to actual clients.
Delivery Report	Report to indicate that QA took place on delivered unit and that a Complete health check was performed at CubeSpace before shipment.

3. Configurability

The external electrical, mechanical, and communication interfaces can be configured[1] based on customer needs.

The element used to interface with a client's satellite OBC is called the CubeDoor. A client specific addendum document will be provided if applicable, detailing the CubeDoor designed for a specific order, if it is not the standard offerings described in this document. The standard CubeDoor interface is the PC104 based standard. Also refer to [1] for more detailed information.

The four corner-rail mounting system commonly used in CubeSats can also be accommodated with e.g. threaded holes allowing for the enclosure of the core CubeADCS stack to be bolted into position.

The element used to interface with the other CubeProducts (sub systems) as per client mission requirements is called the CubeConnect. A client specific addendum document will be provided, if applicable, if it is not the standard offerings described in this document.

In some cases, the CubeDoor and CubeConnect might not have to be two separate PCBs and both functions can be included in a single PCB. In these cases, it will be known as the CubeConnect only.

There are a number of optional features which the client can choose to include in the CubeADCS for their satellite. The client can select these options in the CubeADCS Client Mission Overview document (see [2]).

3.1. Optional features

The following interfaces can optionally be added to CubeADCS:

3.1.1. Power regulation

The standard CubeADCS requires 3V3, 5V and battery voltage (6.2V to 17.4V) power rails to operate. The CubeADCS provides the option to the user to supply these power rails externally or to only supply the battery voltage power rail. From the battery voltage power rail, local power regulation of 3.3V and 5V rails is possible on the CubeADCS[2]. This reduces the number of connections required to the CubeADCS.

3.1.2. Enable control line

The CubeADCS can expose an enable control line to the satellite bus. This is a logic input to the CubeADCS. This will allow a master device like an OBC to power down the CubeADCS by pulling the Enable line low. The Enable line will turn off the power switches to the CubeADCS. The Enable line should not be pulled high, the Enable line is internally pulled high by the CubeADCS if battery power is applied. The Enable line should be driven with an open drain GPIO connection. The line should only be pulled low by the GPIO.

3.1.3. GNSS and PPS interface

A UART interface along with an LVDS or CMOS 1PPS input is available on the CubeADCS to allow communication with a client supplied GPS. This allows the CubeADCS to directly receive GNSS data packages and accurate real time knowledge information and a 1PPS signal to synchronize. The GNSS position vector can also be used to augment the SGP4 orbit propagator for a better than 100-meter accurate instantaneous satellite position vector.

[1] Terms and conditions apply. Please contact CubeSpace for more information.

[2] Regulation power losses should be considered when assessing the power consumption values in this document.

CubeSpace has some experience with the interfacing to the GPS units indicated in Table 3 and could assist a prospective client on how to setup and configure the GPS via the OBC, to allow the GPS UART communication and 1PPS interfacing to the CubeADCS in the required format.

3.2. Harness lengths

Harness lengths are difficult for a typical client to indicate accurately as the start of a project. Typically CubeSpace will supply a detailed wiring / harness list documenting all aspects of harnesses internal to the CubeADCS soon after the final ADCS configuration is baselined. Within said document, CubeSpace will request the client to indicate harness lengths based on the final placement of the CubeADCS subsystems within the satellite and the clients harness routing scheme.

Several different harness lengths to actuator and sensor nodes are available for the user to choose from, these options are also made available in the CubeADCS Client Mission Overview document (see [2]).

3.3. Actuator sizing

CubeADCS is suited for nanosatellites and smaller microsatellites. While the ADCS computer and the sensors can be used for any satellite, the actuators must be scaled based on the satellite's size, deployable structures, and required manoeuvrability.

Both the CubeWheel and CubeTorquer are available in a range of sizes and can be selected based on mission needs. For 6U and smaller satellites, up to 3 reaction wheels and 3 magnetorquers can be included in the integrated CubeADCS stack. For larger satellites, these actuators must be mounted externally.

Table 5 provides a rough guideline for selecting between the various actuator sizes available for CubeADCS depending on satellite size and desired performance.

Table 5: Actuator specifications

SATELLITE SIZE	CUBETORQUER	CUBEWHEEL (PER WHEEL)	MOUNTING
Up to 3U	0.2 Am^2 (X) [CR0002] 0.3 Am^2 (Y/Z) [CR0003]	Max torque: 2 mNm Max momentum[a]: 1.77 to 5.7 mNms [CW0017 – CW0057]	All actuators integrated in CubeADCS stack if only 3 wheels are used. If 4 wheels (pyramid) are used, wheels must be mounted externally while torquers can be mounted externally or internally.
6U to 12U	0.4 to 1.0 Am^2 (all axes) [CR0004-CR0010]	Max torque: 7 mNm Max momentum[a]: 5.7 to 16.2 mNms [CW0057 – CW0162]	

[a] Momentum values are given for a 6000-rpm maximum wheel speed at minimum motor supply voltage. Higher momentum can be achieved with higher motor supply voltage.

3.3.1. Wheel configuration

Two configurations of reaction wheels are possible in CubeADCS, depending on mission needs. Table 6 details both of the available configurations.

Table 6: Wheel configurations

CONFIGURATION	DESCRIPTION	TYPICAL USE CASE
3-Axis	Three orthogonal reaction wheels are used to acquire full 3-axis control.	Earth-based pointing or target tracking, sun pointing, inertial pointing, satellite tracking

10 Elektron Rd, Techno Park, Stellenbosch, 7600, South Africa

CONFIGURATION	DESCRIPTION	TYPICAL USE CASE
4-Wheel	Four reaction wheels, placed in a pyramid configuration, are used to acquire full 3-axis control. Wheels are biased to an offset speed, thus avoiding zero-crossings. If one of the wheels fail, 3-axis control is still available.	Same as 3-Axis, but with more stability and redundancy.

3.4.Sensor selection

The selection of ADCS sensors is largely driven by the performance required from the ADCS. All standard CubeADCS solutions are equipped with one deployable CubeMag magnetometer, two gyroscopes (one high performance, one low performance) fitted on the CubeComputer, and one CubeSense Sun fine sun sensor. CubeSense Earth (up to 2) can optionally be added to provide increased performance in eclipse. A star tracker (either CubeStar or third-party (see Table 3) can also be added for missions requiring very high performance throughout the orbit.

Several additional (optional) sensors can be equipped on a CubeADCS unit:

Coarse sun sensors (photodiode array) → Up to 10 single-axis photodiodes can be added to a CubeADCS to provide a robust (but coarse) sun vector measurement using negligible power.
CubeMag Compact (redundant magnetometer) → Magnetometers are critical to the functioning of CubeADCS. CubeMag Compact can therefore be added to provide redundancy if the primary CubeMag is contaminated with noise or in the (unlikely) case of primary CubeMag failure.
Additional CubeSense Sun sensors → In cases where the sun beta angle (i.e. the angle between the orbit plane and the sun) is not fixed or when the satellite must fly with various attitudes, having multiple fine sun sensors is often desired. Up to 4 CubeSense Sun sensors can be connected to the CubeADCS core stack, depending on mission needs.

Table 7 shows the available sensor suites for CubeADCS.

Table 7: Sensor suites

CONFIGURATION	SENSOR(S)[A]					INCLUSION	PERFORMANCE[B]	
	MTM	GYR	FSS	EHS	STR		Sunlight	Eclipse
Base	x	x	x			Always	High	Low to moderate
Base + EHS	x	x	x	x		Optional	High	High
Base + EHS + STR	x	x	x	x	x	Optional	Very high	Very high

[a]MTM = magnetometer (typically the CM and / or CMC),
GYR = gyroscope,
FSS = fine sun sensor (typically the CS),
EHS = earth horizon sensor (typically the CIR,
STR = star tracker (typically the CT).

[b] Performance is also dependent on satellite size/layout and orbit. Performance is determined by CubeSpace with a simulation on a case-by-case basis.

4. Coordinates definition

It is important to understand the coordinate definitions of the CubeADCS, as later sections rely on this understanding. Mounting configuration and attitude reference angles are interpreted based on this definition.

The CubeADCS defines the satellite body coordinate (**SBC**) frame, which is "fixed" to the satellite body. When the satellite has a nominal attitude (zero pitch, -roll and -yaw) the **SBC** will coincide with the orbit reference coordinate system (**ORC**).

4.1.1. Orbit reference coordinate (ORC)

The **orbit reference coordinate (ORC)** frame, notated as $\mathbf{X}_{ORC}$, $\mathbf{Y}_{ORC}$, and $\mathbf{Z}_{ORC}$, is defined throughout the CubeADCS literature as per Table 8 and Figure 11 below.

Table 8: CubeADCS Orbit reference frame notation

AXIS	POINTING DIRECTION
X_{ORC}	Flight Direction
Y_{ORC}	Orbit anti-normal direction
Z_{ORC}	Nadir direction

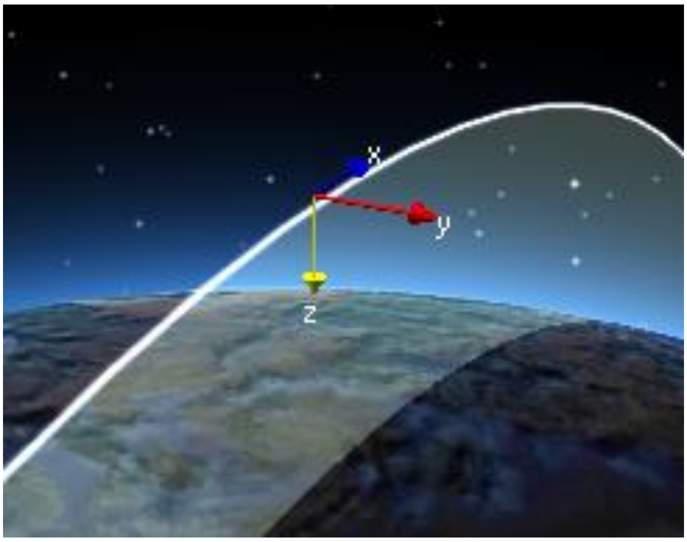
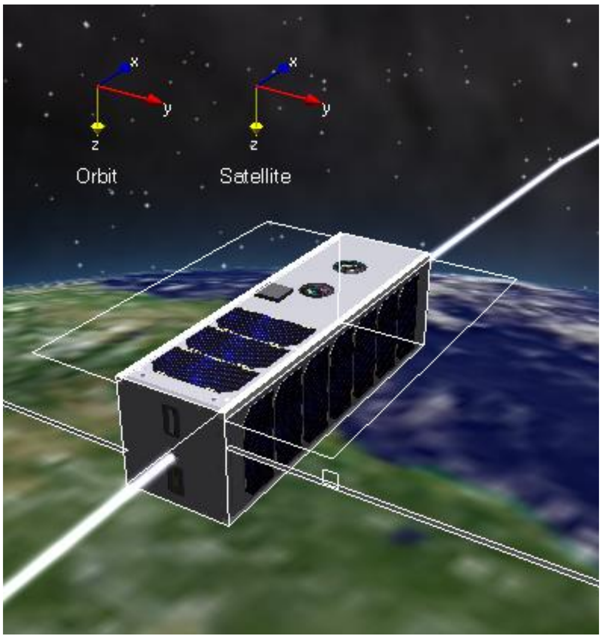


Figure 11: Orbit Reference Coordinate (ORC) frame

4.1.2. Spacecraft body coordinates (SBC)

The **spacecraft body coordinate (SBC)** frame is notated as $\mathbf{X}_{SBC}$, $\mathbf{Y}_{SBC}$, and $\mathbf{Z}_{SBC}$, and must be "fixed" to the satellite such that when roll-, pitch- and yaw angles are zero, the X_{SBC} axis points along the velocity direction, Y_{SBC} points in the orbit anti-normal direction and Z_{SBC} points towards nadir. For non-zero attitude angles, the **SBC** will rotate with respect to the **ORC**, as depicted in Figure 12.



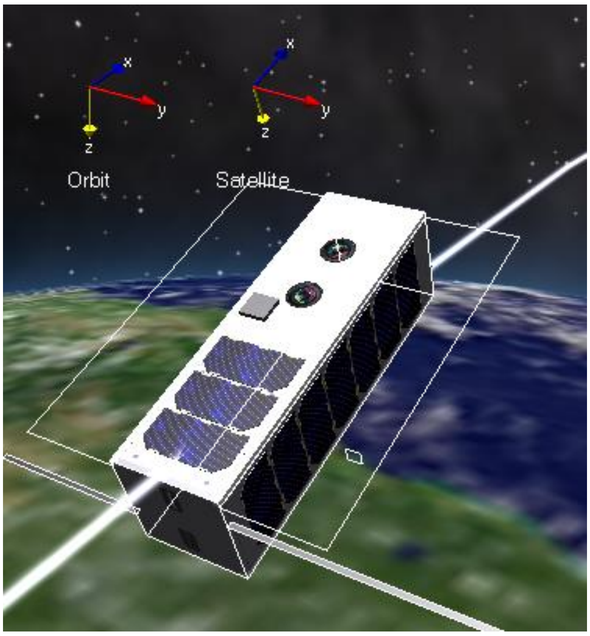


Figure 12: Satellite (spacecraft) Body Coordinate frame, relative to the Orbit Reference Coordinate frame for zero roll, pitch and yaw (left image) and a 20° pitch angle (right image)

4.1.3. CubeADCS defined SBC versus mechanical and CAD reference frames.

It is often the case that satellite designers use a spacecraft's axes definition for CAD or mechanical ICD purposes that may be different from the CubeADCS defined **SBC**. It is important to note that the ADCS does not attempt to translate or transform between a customer's CAD coordinate frame and the ADCS defined SBC. Instead, the ADCS defined SBC must be the only coordinate frame that is considered when specifying sensor or actuator mounting configurations, and when interpreting attitude angles.

4.1.4. Attitude angles convention

The CubeADCS follows an Euler 2-1-3 convention for roll, pitch and yaw angles.

4.1.5. Sensor/actuator mounting configuration

All actuators and sensors each have their own local coordinate systems. Each sensor and actuator mounting must be defined relative to the SBC through a transformation matrix. This means that the transformation matrix for each actuator or sensor should be known.

The mounting information is part of the configurable settings for the ADCS and must be specified for correct operation of the unit. The CubeADCS Client Mission Overview (see reference [2]) indicates the recommended mounting orientation for sensors and actuators while also allowing non-standard client configurations.

5. General satellite layout and flight orientation

When designing a satellite and its mission, the satellite's physical layout relative to the flight orientation is critical to the correct operation of the ADCS.

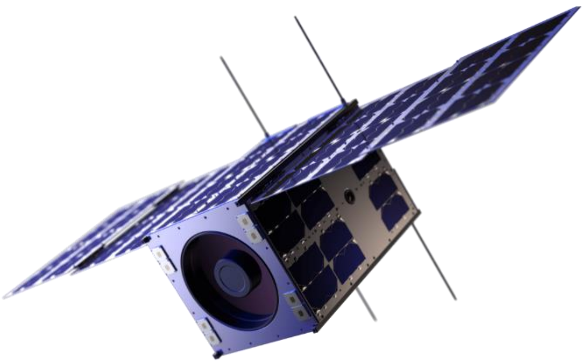
By keeping attitude disturbances at a minimum, it is easier to ensure that the CubeADCS will maintain a stable attitude, and to meet pointing requirements. It will also ensure minimal power consumption as actuators will need lower actuating torque.

The attitude disturbances on a satellite body are a function of the shape of the satellite, including deployable elements, and the mass distribution inside the satellite body. Attitude disturbances is a comprehensive subject, and this section only lists a few points to consider that can aid in attitude stability.

It should also be noted that attitude requirements may differ depending on the phase of the orbit that the satellite is in. During eclipse it is desirable to minimize power usage, and a passively stable flight orientation which experiences very little disturbance torque will be beneficial. This will require the minimum amount of energy from the ADCS to maintain attitude.

During sunlight parts of the orbit the aim will be to point the solar panels towards the sun when no target tracking, or other manoeuvres, are required. The less disturbance torques there are on the satellite body, the less power and actuating torque will be required of the ADCS to properly stabilise the satellite.

In general, a symmetric satellite body causes smaller attitude disturbances. Figure 13 provides an example of a symmetric solar panel layout with low attitude disturbance, compared to an unfavourable layout that will lead to poor ADCS performance in LEO.



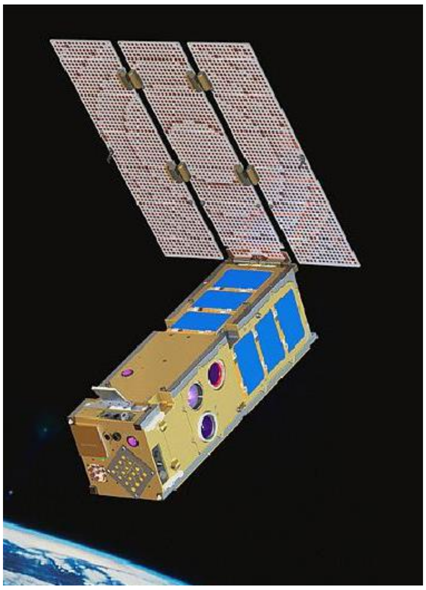


Figure 13: Example of symmetric solar panel layout with small attitude disturbances (left) [image credit EnduroSat] and unsymmetric layout with large attitude disturbances (right) [image credit ESA]

In some cases, it may be beneficial to choose a satellite layout with induced aerodynamic or gravity gradient torque that will aid in passive attitude stability.

5.1. Passive aerodynamic stability

Passive aerodynamic stability is achieved if the natural aerodynamic torque will rotate the satellite back to nominal attitude. The ADCS thus does not have to overcome the aerodynamic disturbance torque to bring it to nominal attitude. An example of an aerodynamically stable 3U CubeSat is shown in Figure 14. The key characteristics of such a satellite layout are:

- **Minimum drag**, i.e., smallest projected area is normal to the nominal flight direction.
- **Aerodynamic symmetry**, i.e., projected areas are symmetric around the centre of mass (CoM) and are aligned to the centre of pressure (CoP) along the flight velocity vector. This is a hard requirement for a Y-Momentum stabilised satellite with inherent passive aerodynamic stability.
- **Passive aerodynamic stability**, i.e., ensure the CoP is behind the CoM. This is a hard requirement for a Y-Momentum stabilised satellite.

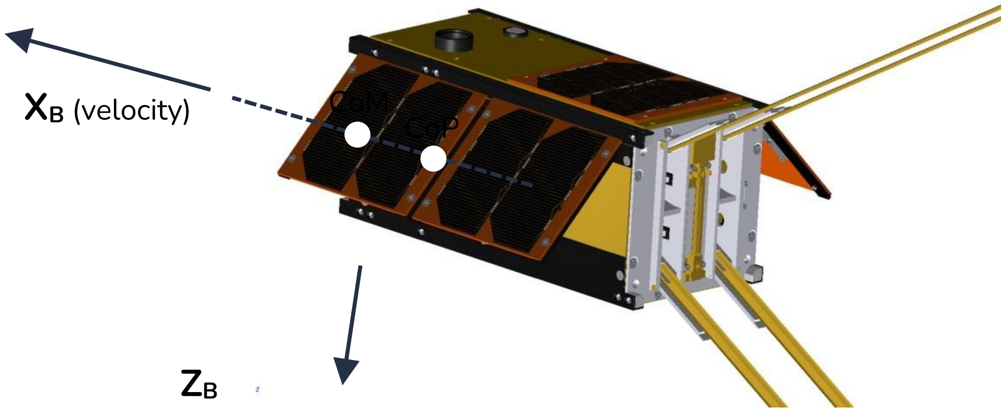


Figure 14: Passive aerodynamic stability with lowest drag

It should be noted that an aerodynamically stable layout, with CoP trailing behind the CoM, might still prove to be difficult to control if the ADCS has to perform attitude manoeuvres away from the nominal orientation.

5.2. Gravity gradient stabilisation

If a satellite has long deployed booms for scientific payloads it is preferred to deploy these towards zenith and/or nadir (Figure 15) for passive stability. This is a hard requirement for a Y-momentum stabilised satellite.

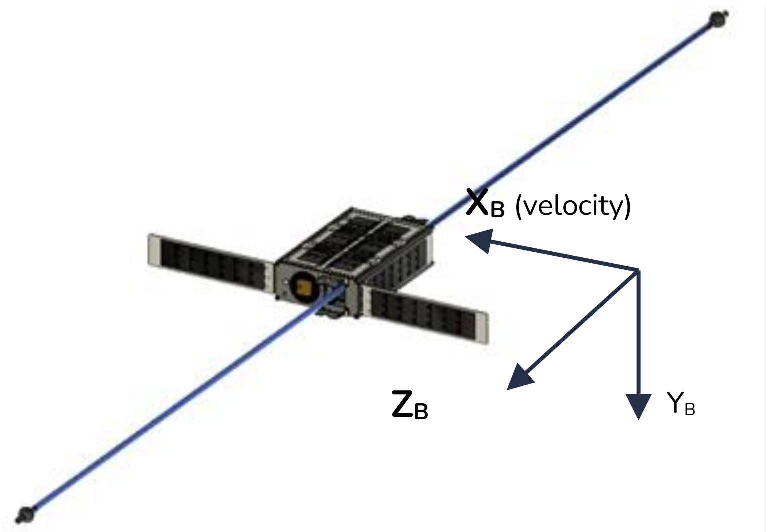


Figure 15: Deployable boom direction for passive gravity gradient stability

5.3.Spin Modes and Inertia Requirements

For the ADCS to achieve a stable spinning motion it is required to spin about the principal axis with either the smallest or the largest moment of inertia. The two spin control modes which will result in a Y-Thomson or Z-Thomson spin will thus only work if the Y_B axis is not an intermediate axis (for Y-Thomson spin) or the Z_B axis is not (for Z-Thomson spin).

It is further possible to select control modes that will process the momentum vector of a spinning satellite to point towards the sun. Such a Y-sun or Z-sun spin control mode is advantageous as a safe mode since it uses magnetic control only with minimal sensor inputs. Care must be taken when designing the satellite and solar panel layouts, with regard for the orbit and sun conditions to ensure that such a safe mode can be used.

The CubeADCS further requires that the moment of inertia for the chosen spin axis is different from the other axes' moments of inertia by at least 10%. If this is not the case, it might still be possible to perform the intended spin, but it will require that either the Y_B aligned reaction wheel (for Y-Thomson spin) or Z_B aligned wheel is commanded to a bias value. In cases where the reaction wheels are mounted in pyramid configuration, an open-loop momentum command will have to be applied to the reaction wheel pyramid to result in a bias momentum, which results in more than one wheel running at the same time. Such a reaction wheel or momentum bias implies that it is no longer a pure magnetic control mode and might make less sense for a "safe" mode.

The CubeADCS can transition into a Y-momentum stabilized control mode, in which case a single Y_B aligned wheel is used (or a Y-axis momentum is applied to the reaction wheel pyramid) to stabilize the attitude of the satellite with control of the pitch angle only. In this case, it is required to transition from a Y-Thomson spin to Y-momentum stabilized control.

6. Sensor and actuator placement

In general, all CubeSpace's attitude sensors must be mounted in optimal locations and orientated correctly to maximize their ability to take valid measurements and to minimize possible disturbances that will compromise their measurement accuracy. Attitude actuators must be placed in locations far enough from sensitive payloads or sensors that can be disturbed by their magnetic fields or vibrations caused by the unbalance forces and torques of rotating discs. Details are discussed in the following sub-sections.

6.1. CubeMag deployable and compact - Magnetometers

3-Axis magnetometers are used to measure the small geomagnetic field vector direction to extract attitude information They are very sensitive devices that can easily be disturbed by any satellite bus generated magnetic fields. It is therefore important to ensure the following conditions are met when deciding on the optimal mounting location for the CubeMag(s):

- At least 10 cm from solar cells or panels, see chapter 7.5 on magnetic cleanliness.
- At least 10 cm from harnesses carrying varying large currents.
- At least 15 cm from CW0057 and CW0162 reaction/momentum wheels with rotating magnetic fields. For CW0017, a distance of 10 cm is allowable.
- As far as possible away from any permanent magnets.
- Far enough from any magnetic torque rods or torquer coils to prevent potential saturation or -bias disturbances from the remanent dipoles of torque rods.
- As far as possible from metals with magnetic properties (e.g., stainless steel fasteners) – metal that can be magnetised will bend the geomagnetic field lines and cause distorted measurements. Non-magnetic fasteners, e.g., brass, copper, titanium, or aluminium are preferred close to a magnetometer sensor.
- As far as possible from any magnetic shielding material (e.g., Mumetal), as this can block the local geomagnetic field.

6.2. CubeSense Sun – Fine Sun sensors

Ensure a hemispherical (180°) FoV when defining the optimal mounting location for the CubeSense sun sensor. Avoid any deployable elements, e.g., antennae, booms, or solar panels in the FoV as these can cause reflections of the sun and give false sun vector detections. If unavoidable, deployable parts that will be visible in the sensor FoV must be coated with a non-reflective coating to ensure minimal reflections that will not be detectable by the sun sensor.

Orientate the sun sensor boresight at a chosen mounting location to ensure an optimal sun vector measurements at nominal attitude (i.e., zero roll, -pitch and -yaw angles) or during sun tracking (i.e., in the same direction as the deployable solar panel normal vector). For sun-synchronous orbits the sun vector angle to the orbit plane will be constant (depending on the LTDN or LTAN time) and a single CubeSense Sun sensor can be placed to always see the sun during the sunlit part of each orbit.

For other orbit inclinations, e.g., the ISS orbit, the orbit plane angle to the sun will drift continuously and the sun angle can vary between ±180° throughout the orbital year. For a single CubeSense sun sensor in such an orbit, the boresight direction will be best when pointing in the zenith direction, i.e., sun vectors below the local horizon cannot be measured.

6.3. CubeSense Earth – Earth Horizon Sensor

The CubeSense Earth sensor operates in the thermal infrared (IR) spectrum and must be mounted with its boresight pointing towards the earth's horizon, i.e., at a horizon angle from the nadir direction (see Eq.3.1) depending on the orbit altitude. For example, for a 500 km circular orbit the earth horizon is found when pointing 68° from nadir. This is also then the required tilt angle that should be used for the CubeSense Earth sensor mounting, for this orbit.

The earth horizon angle at the equator, depending on the orbit altitude *h*:

$$\theta_{hor} = asin\left({}^{R_E}/_{(R_E + h)}\right) \quad 3.1$$

with,

R_E = Equatorial radius of 6378 km

h = Orbit altitude in km

The FoV of CubeSense Earth is 90° x 72°. It measures the earth horizon curvature to determine the roll and pitch angles It is best to mount the sensor with the widest part of its FoV horizontally. The latter mounting orientation will give a measurement range of ±36° to the vertical boresight angle and allow at least ±45° for rotations of the horizon curvature around the boresight.

Ensure that CubeSense Earth has an unobstructed FoV to the earth horizon.

6.4. CubeStar - Star tracker

CubeStar has a wide 42° circular FoV for bright star detection. It is important to ensure that the earth will not be in the FoV during star identification and tracking, even in eclipse. The earth glow in especially the upper region of the atmosphere can produce many false star detections if it lies in the CubeStar's FoV. For potential star detection during the sunlit part of the orbit, the sun must always be behind the CubeStar lens, i.e., at angles >90° from the sensor boresight when no additional baffle is used. The preferred mounting location will be to ensure boresight pointing as much as possible towards the zenith direction and away from the sun during nominal operational attitude.

CubeStar must have an unobstructed FoV from any deployable parts to ensure that no stars that are still in the FoV will disappear from detection during star tracking, and to prevent reflections that cause false star identifications.

6.5. CubeWheel - Reaction and Momentum wheels

It is important to mount any wheels for attitude control as far as possible from magnetically sensitive magnetometers, imaging payloads, star tracker sensors and from rate sensors. In the case of imaging sensors and the rate sensors, mechanically induced vibration disturbances due to static unbalance forces, dynamic unbalance torques and bearing noise can cause blurring of images and an increase in rate measured noise.

For a satellite with a very high-resolution imaging payload, the satellite designer should consider the use of vibration damping fasteners for the wheels. It must also be standard practice to mount an imaging payload and a star tracker on an optical bench to a mechanically separate them from the rest of the satellite bus, especially the spinning rotors of wheel actuators.

6.6. CubeRod - Magnetorquers

CubeSpace torquer rods are heat treated to have very small residual moment, but care should still be taken to mount magnetically sensitive payloads and magnetometer sensors as far as possible from them. Although magnetometer measurements will only be taken during windows of magnetorquer inactivity, they can still be disturbed by the residual magnetic moments and within the magnetic decay time of these magnetorquers.

7. CubeADCS operation

The CubeADCS is operated, to achieve satellite mission objectives, by commanding different estimation and control modes. This section provides a brief description of the available modes, and for which purposes they might be used.

Full details are available in the form of the CubeADCS User Manual and CubeADCS commissioning and Operations Manual, available after ordering an ADCS.

7.1. ADCS estimation modes

The *Estimation Mode* determines which sensor measurements are used and what information is estimated. The current estimation mode is changed by telecommand. Although more modes are available, the primary estimation modes are shown in Table 9, as well as which sensors are used per Estimation Mode.

Table 9: Primary estimation modes.

ESTIMATION MODE	DETAIL	SENSORS USED	ESTIMATED INFORMATION
Gyro rates	Angular rate vector measured directly from on-board rate sensor	X,Y,Z –axis rate sensors	X,Y,Z angular rates
Magnetometer rate filter	Estimation of angular rate vector from successive magnetometer measurements	Magnetometer	X,Y,Z angular rates
Full-state EKF	Estimation of attitude and angular rates by EKF using all available sensor measurements	Magnetometer; Sun sensor; Nadir sensor; Star tracker	Roll, Pitch & Yaw angles; X,Y,Z angular rates
Gyro EKF	Estimation of attitude and gyro bias by EKF using all available sensor measurements.	X,Y,Z–axis rate sensors; Magnetometer; Sun sensor; Nadir sensor; Star tracker	Roll, pitch & Yaw angles; X,Y,Z angular rates; X,Y,Z gyro bias

7.2. Control modes

Control mode changes are (also) achieved by sending a telecommand to the ADCS. The available control modes are grouped by their function.

- Detumbling and safe-mode magnetic spin control (uses only magnetorquers)
    - Magnetic detumbling (normal and high-initial rate detumbling up to 1000°/s)
    - Spin stabilized (Y-Thomson and Z-Thomson)
    - Safe-mode sun-pointing spin
- Gravity-gradient stabilization
    - Magnetic gravity-gradient stabilized (magnetorquers only)
    - Yaw control using Z_B reaction wheel
- Momentum wheel stabilized
    - Y_B axis aligned momentum wheel stabilized
- 3-axis reaction wheel control
    - RPY reference following (set to zero roll, pitch and yaw reference for nadir pointing)
    - Ground target tracking
    - High-gain target steering (with optional sensor feedback)

- Sun-tracking
- Ground target antenna pointing
- Inertial vector tracking (i.e. pointing to a star)
- Moon tracking
- Target satellite tracking
- Combined optimized roll or yaw with sun or target following

7.3.Automatic Recovery Mode

The ADCS accepts a setting for automatic recovery mode, which is a subset of the above control modes. If enabled, the ADCS will automatically transition from any initial condition to the automatic recovery mode.

This setting should only be used after commissioning of the ADCS.

7.4.Configuration and Reference Values

The CubeADCS makes use of configuration settings to govern the behaviour of the control and estimation logic. Table 10 lists the configurable settings that affect estimation and control behaviour, that can be changed by telecommand (and read using a telemetry request).

Table 10: ADCS configuration settings

SETTINGS GROUP	CONTENT
Default mode configuration	Power-on default control mode and operational state
Mounting configuration	Mounting directions and mounting angles that define the mounting transforms between sensor/actuator coordinate frames and Spacecraft Body Coordinate (SBC) frame
Magnetometer in-orbit calibration correction configuration	In-flight calibration values for magnetometer
ADCS controller configuration	Controller gains and parameters
ADCS estimator configuration	Estimator system noise and sensor noise covariances Flags to control sensor use in estimators
ADCS satellite configuration	Satellite moments of inertia and products of inertia Vector directions to influence controller pointing behaviour
Satellite orbit parameter configuration	Orbital elements for satellite orbit
Target satellite orbit parameter configuration	Orbital elements for target satellite orbit
Node selection configuration	Selection flags to control which sensors are to be used, if multiple sensors of the same type are present
Wheel configuration	Wheel hardware configuration (wheel sizes and parameters, and mounting selection – pyramid vs. three orthogonal wheels)
Magnetorquer configuration	Magnetorquer hardware configuration (torquer strength and maximum on-time)
Mag sensing element configuration	Selection between primary and redundant magnetometer sensing elements

Configuration values are stored using non-volatile memory and persists between power cycle and resets.

The control modes of the ADCS further make use of “Reference Values”, as parameters to the controllers. These include:

- Roll, pitch and yaw reference angles
- Ground target location (latitude, longitude, and altitude)
- Inertial pointing vector

Reference values do not persist through power cycle or resets and should ideally be commanded prior to setting the relevant control mode.

7.5.Stowed and deployed configuration

The moments of inertia and the products of inertia for a specific satellite must be correctly set for the ADCS to function nominally. If any deployable structure on the satellite is activated, the MOI and POI of the satellite will change. It is then required to change the satellite moment of inertia configuration by sending a telecommand. Such telecommand will be issued by the OBC, however all telecommands to change ADCS configuration will likely originate from the ground station and mission operations during commissioning.

7.6.Orbit parameter

The orbit SGP4 parameters must be regularly updated to account for a changing orbit. This is especially important at LEO altitudes. This is again done through the OBC however the command will originate from the ground segment since it will be required to obtain the latest TLEs from www.celestrak.org or www.space-track.org.

It is recommended that the TLEs be updated daily during commissioning, and at least once a week, thereafter. Figure 16 below gives an indication of the estimated position error that can be expected when using aging TLEs.

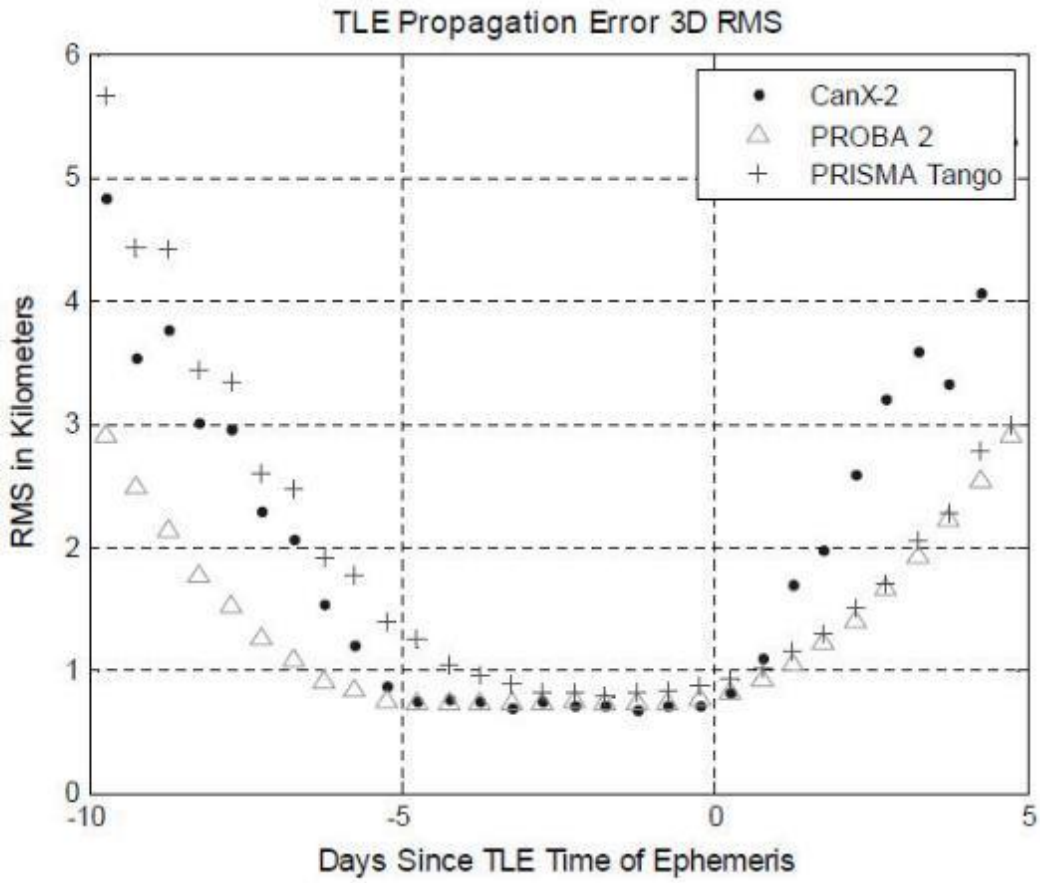


Figure 16: Example of TLE Time since Epoch error for different satellites.

8. Magnetic cleanliness

As the CubeADCS makes use magnetometers for attitude estimation, active magnetic control (interaction with the geomagnetic field) to detumble the satellite and dump angular momentum built-up on the reaction/momentum wheels, the satellite designer must ensure that the satellite is magnetically as clean as possible without any large internal magnetic dipoles. These dipoles can be caused by:

- The configuration (connections) of the solar cells on the solar panels. This can be compensated for by back wiring loops on the solar panels or the use of paired solar panels on the same facet with a mirrored configuration to cancel possible current loops. An uncontrolled satellite can easily spin up to very high rates if left unattended over a period, due to these magnetic moments when the sun illuminates the solar panels. The applied principal here is like the working of an electric motor, i.e., a torque is produced by a rotating current loop (illuminated solar panel) in the geomagnetic field.
- Internal permanent magnets, e.g., thruster valve solenoids, scientific payloads, magnetised metal components, etc.
- Loop currents in harnesses, e.g., battery or regulated voltage bus supply currents from the EPS.

If a magnetic dipole is large enough and fixed in the satellite body frame, this dipole will track the geomagnetic field lines like a compass needle. It can specifically cause large attitude disturbances to a Y-Momentum stabilised satellite, preventing it from having small roll and yaw nutation angles. These dipoles can also cause significant disturbances to magnetometer measurements of the geomagnetic field. Magnetically sensitive satellites must preferably be degaussed before launch.