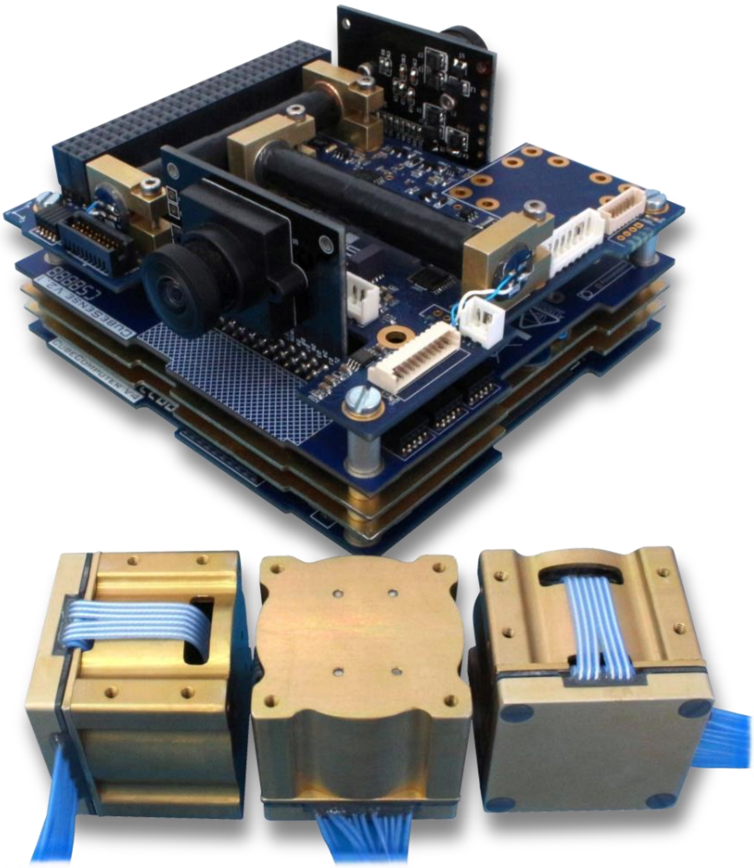
CubeADCS 3-Axis

The complete ADCS solution for 3-axis control



Commissioning Manual

Contact Us
Phone : +27 21 808 9499
E-mail : info@cubespace.co.za
Web : www.cubespace.co.za
Facebook : /CubeSpaceADCS
Twitter : @CubeSpace_ADCS

Physical Address
CubeSpace
The LaunchLab
Hammanshand Road
Stellenbosch, 7600
South Africa

Electronic Systems Laboratory

UNIVERSITEIT STELLENBOSCH UNIVERSITY

Document	CubeADCS 3-Axis Commissioning Manual
Version	3.06
Domain	Public
Date modified	2 March 2018
Approved by	Name: Mike-Alec Kearney
	Signature:

Document Version History

Version	Responsible person(s)	Pages	Date	Description of change
3.0	MK	ALL	20/03/2017	V3 First draft
3.01	WHS	ALL	05/04/2017	V3.01 First Release
3.02	WHS	ALL	11/07/2017	V3.02 Second Release
3.03	CJG	ALL	26/07/2017	V3.03 Format updates
3.04	MK	ALL	27/07/2017	Accept/Reject team changes
3.05	WHS	18	16/01/2018	Update Fast Detumbling modes
3.06	HW	4	02/03/2018	Fixed reference to CubeStar Ref. Man.

Reference documents

This document is to be used in combination with the following documents

Reference	Document name	Document version
R01	CubeADCS – Reference Manual	V3
R02	CubeADCS – User Manual	V3
R03	CubeStar – Reference Manual	V1

List of Acronyms/Abbreviations

ACP	ADCS Control Program
ADCS	Attitude Determination and Control System
CSS	Coarse Sun Sensor
ESD	Electrostatic Discharge
I^2C	Inter-Integrated Circuit
MCU	Microcontroller Unit
MEMS	Microelectromechanical System
OBC	Onboard Computer
PCB	Printed Circuit Board
RTC	Real-Time Clock
SBC	Satellite Body Coordinate
SPI	Serial Peripheral Interface
TC	Telecommand
TLM	Telemetry
UART	Universal Asynchronous Receiver/Transmitter

Table of Contents

1 Introduction

This document describes the activities related to the commissioning of a CubeSpace ADCS module in flight.

Some of the data and plots contained in this manual were obtained through commissioning of the QB50 precursor 2U CubeSat satellites and other plots using a Matlab/Simulink simulation of a typical 3U CubeSat satellite. In the former case, credit goes to Innovative Solution in Space B.V. (ISIS) for providing the data.

The ADCS commissioning milestones are summarized in the following table.

Table 1 Commissioning steps

no.	Step	Paragraph
1	Determine initial angular rates	3
2	Initial detumbling	4
3	Continued detumbling to Y-Thomson	4
4	Magnetometer deployment	5
5	Magnetometer calibration	6
6	Angular rate and pitch angle estimation	7
7	Y-wheel ramp-up test	8
8	Initial Y-momentum activation	9
9	Continued Y-momentum activation and magnetometer EKF	9
10	CubeSense sun/nadir commissioning	10
11	EKF activation with sun and nadir measurements included	10
12	CubeStar star tracker commissioning	11
13	EKF activation with star vector measurements	11
14	Zero-bias 3-axis reaction wheel control	12
15	EKF with Rate gyro measurements, inclusion of star tracker measurements	12
16	Sun tracking 3-axis control	13
17	Ground target tracking controller	14
18	GPS receiver commissioning	15

2 ADCS command and data requirements

The ability to commission and operate the ADCS places some requirements on the satellite and ground station to download data and upload commands.

2.1 Commands

Nominal operation of the ADCS should involve very few telecommands (set estimation & control mode, set enabled state) but throughout commissioning it will be necessary to send other commands in the command specification [R01].

2.2 Telemetry

Ideally all telemetry points from the ADCS should be observable by real-time telemetry request, but the capability should also exist to log data to non-volatile storage over extended periods (typically an orbit) so that it can be downloaded whenever the satellite is in range of the ground station. The latter is often called whole orbit data (WOD).

The telemetry frames that should be logged will depend on the current commissioning or operating phase. The telemetry that should be logged will be a selection of telemetry frames TLM ID 140-189 [R01], The ADCS can log the previously mentioned data to on-board SD card by specifying a mask selection (TC ID 104-105). It is also possible to obtain the same data from the ADCS using fewer I2C transactions but longer data messages.

The ADCS data that will be required throughout commissioning is listed in the table below:

Table 2 Telemetry logging requirements

TLM ID	TLM name	Required minimum sampling period (s)										
		Determine initial angular rates	Initial detumbling	Continued detumbling to Y-Thomson	Magnetometer deployment	Magnetometer calibration	Angular rate and pitch angle estimation	Y-wheel ramp-up test	Initial Y-momentum activation	Continued Y-momentum activation	CubeSense sun/nadir logging and test	EKF activation
140	Current Unix Time	10	10	10	10	10	10	10	10	10	10	10
145	Current ADCS State	10	10	10	10	10	10	10	10	10	10	10
146	Estimated Attitude Angles	-	-	-	-	-	10	1	10	10	1	1
147	Estimated Angular Rates	10	10	10	1	10	10	1	10	10	10	10
148	Satellite Position (LLH)	-	-	-	-	-	-	-	10	-	-	-
149	Satellite Velocity (ECI)	-	-	-	-	-	-	-	10	-	-	-
150	Satellite Position (LLH)	-	-	-	-	-	-	-	10	-	-	-
151	Magnetic Field Vector	1^*	10	10	1	10	10	10	10	10	10	10
152	Coarse Sun Vector	-	-	-	-	-	-	-	-	-	-	-
153	Fine Sun Vector	-	-	-	-	-	-	-	-	-	1	10
154	Nadir Vector	-	-	-	-	-	-	-	-	-	1	10
155	Rate Sensor Rates	10	10	10	1	10	10	1	10	10	10	10
156	Wheel Speeds	-	-	-	-	-	-	1	10	10	10	10
157	Magnetorquer Command	-	10	10	-	-	-	10	10	10	10	10
158	Wheel Speed Commands	-	-	-	-	-	-	10	10	10	10	10
159	IGRF modelled Vector	-	-	-	-	10	-	-	-	-	-	10

160	Modelled Sun Vector	-	-	-	-	10	-	-	-	-	10	10
161	Estimated Gyro Bias	-	-	-	-	-	-	-	-	-	-	-
162	Estimated Innovation	-	-	-	-	-	-	-	-	-	-	10
163	Quaternion Error Vector	-	-	-	-	-	-	-	-	-	-	-
164	Quaternion Covariance	-	-	-	-	-	-	-	-	-	-	10
165	Angular Rate Covariance	-	-	-	-	-	-	-	-	-	-	10
166	Raw Nadir Sensor	-	-	-	-	-	-	-	-	-	1	10
167	Raw Sun Sensor	-	-	-	-	-	-	-	-	-	1	10
168	Raw CSS1 to CSS6	1*	10	10	1	10	10	10	10	10	-	-
169	Raw CSS7 to CSS10	1*	10	10	1	10	10	10	10	10	-	-
170	Raw Magnetometer	1*	10	10	1	10	10	10	10	10	10	10
171	CubeSenseCurrents	-	-	-	-	-	-	-	-	-	10	10
172	CubeControlCurrents	10	10	10	1	10	10	10	10	10	10	10
173	WheelCurrents	-	-	-	-	-	-	10	10	10	-	-
174	ADCS Temperatures	-	-	-	-	-	-	-	-	-	-	-
175	Gyro Temperatures	-	-	-	-	-	-	-	-	-	-	-
176	Raw GPS Status	-	-	-	-	-	-	-	-	-	-	-
177	Raw GPS Time	-	-	-	-	-	-	-	-	-	-	-
178	Raw GPS X pos/vel	-	-	-	-	-	-	-	-	-	-	-
179	Raw GPS Y pos/vel	-	-	-	-	-	-	-	-	-	-	-
180	Raw GPS Z pos/vel	-	-	-	-	-	-	-	-	-	-	-
181	Star1 body vector	-	-	-	-	-	-	-	-	-	-	-
182	Star2 body vector	-	-	-	-	-	-	-	-	-	-	-
183	Star3 body vector	-	-	-	-	-	-	-	-	-	-	-
184	Star1 orbit vector	-	-	-	-	-	-	-	-	-	-	-
185	Star2 orbit vector	-	-	-	-	-	-	-	-	-	-	-
186	Star3 orbit vector	-	-	-	-	-	-	-	-	-	-	-
187	Star magnitude	-	-	-	-	-	-	-	-	-	-	-
188	Star performance	-	-	-	-	-	-	-	-	-	-	-
189	Star timing	-	-	-	-	-	-	-	-	-	-	-

*Only if tumbling rates > 20 °/sec are expected, else a sampling period of 10s will be sufficient.

The *ADCS State* telemetry frame (TLM ID 145) contains useful error and status flags and should be included in all ADCS logs. The current and temperature measurements (TLM ID 171-175) can be logged under all steps of commissioning (when needed). The GPS telemetry (TLM ID 176-180) and CubeStar telemetry (TLM ID 181-189) will be useful during commissioning of these sensors.

2.3 Whole Orbit Data logging and synchronization

The ADCS CubeComputer has the ability to log telemetry to a file on its SD memory card. This file can then be downloaded using the protocol described in [R01].

It is also possible to request telemetry from the ADCS at periodic intervals and then log it on the OBC, or someplace external to the ADCS. By logging the telemetry on the ADCS itself, the time consistency of the telemetry is guaranteed. The telemetry will be stored after each processing iteration, thus all of the telemetry entries for one instance will be synchronized. If the telemetry is sampled from the ADCS to be stored externally, then care must be taken to make sure all requested telemetry is of the same epoch. The telemetry that will typically be stored spans multiple telemetry packets and each will have to be requested individually. If the time at which the frames are sampled are close to the beginning of the next ADCS processing iteration it may be possible that one sampled frame contains telemetry from the previous ADCS processing iteration, while the following sampled telemetry frame is of the next ADCS processing iteration – even though the frames were requested in succession.

To avoid such a situation, all required frames should be logged after the ADCS processing has completed for a particular iteration and before the next iteration starts. In order to perform sampling that is synchronized with the ADCS loop, one can use the *ACP Execution State* telemetry frame (TLM ID 220). This telemetry frame will inform if the processing iteration is still taking place or not. The ADCS processing iteration should be fairly short – typically below 200ms. One can thus use the *Time Since Iteration Start* field in the *ACP Execution State* telemetry frame for synchronization. The OBC that samples the ADCS data should wait until the *Time Since Iteration Start* parameter reaches 500ms. The OBC then samples all the telemetry frames that it needs to log, and then the process repeats.

2.4 ADCS status and error flags

The ADCS State telemetry (TLM ID 145) contains a number of error and status flags. State or status telemetry is a reflection of the current ADCS internal state and will update at each processing iteration, regardless if the ADCS State telemetry was requested or not, but error flags are treated differently. If an error occurs, the corresponding error flag will be set, and it will remain set until the ADCS State telemetry frame is read. Reading the ADCS State telemetry will automatically clear the error flags.

This functionality was chosen so that sporadic errors do not get overlooked if the ADCS telemetry is sampled infrequently. If the ADCS State telemetry is read, and an error is present it means that sometime in-between now and the last time the ADCS telemetry was read, an error occurred. If the error is still present the next time the ADCS State is read, it is a persistent error.

This distinction is important to consider when the ADCS state is transmitted to ground, and/or logged to external storage. If the ADCS state is requested from the ground station as real-time telemetry requests, it will be acceptable to simply return whatever data the ADCS returns directly. But it is more likely that the ADCS State telemetry will be buffered somewhere on the OBC before it is sent to ground. In this case one should consider implementing a “latching” mechanism whereby equivalent ADCS error flags on the OBC remain set until a command is given from the ground station to clear them.

When storing the ADCS state telemetry in a log file for later download, one should store the telemetry frame directly as it is received from the ADCS.

The figure below illustrates what happens if an error is registered once in the ADCS loop, and how latching the error in the buffered OBC telemetry will allow the error to be noticed on ground. In the scenario, the OBC samples the ADCS State telemetry every other second. Reading the telemetry frame from the ADCS will automatically clear the error flags internal to the ADCS. But because the data might not be sent to ground immediately, either in the periodic beacon or with a real-time telemetry request, the error occurrence should be latched to on the OBC. When the ADCS State telemetry is then finally sent to ground, the error will be noticed.

Since satellite-to-ground communications are error prone, the error should remain latched until it is explicitly cleared by a telecommand from the ground to the OBC.

time	ADCS loop	ADCS State requested by OBC	OBC log file	OBC Buffered TLM	Beacon/ Real-time TLM	
0	False			False		
1	False	False	False	False		
2	False			False		
3	False	False	False	False	False	
4	True			False		**Error occurs**
5	False	True	True	True		
6	False			True		
7	False	False	False	True	True	
8	False			True		
9	False	False	False	True		
10	False			True		**Cleared by TC**
11	False	False	False	False	False	

Figure 1 ADCS error flag handling

The "latching" mechanism is only required for error flags and should not be used for status flags. The table below indicates which channels in the ADCS State telemetry frame are errors, and which are simply the current state.

Table 3 ADCS State telemetry frame - Error flags vs. status channels

Telemetry channel	State/Error
ADCS Run Mode	
Attitude Estimation Mode	
Control Mode	
CubeControl Signal Enabled	
CubeControl Motor Enabled	
CubeSense Enabled	
CubeWheel 1 Enabled	State
CubeWheel 2 Enabled	
CubeWheel 3 Enabled	
CubeStar Enabled	

GPS Receiver Enabled	
GPS LNA Power Enabled	
Motor Driver Enabled	
Sun above local horizon flag	
CubeSense Communications Error	
CubeControl Signal Communications Error	
CubeControl Motor Communications Error	
CubeWheel 1 Communications Error	
CubeWheel 2 Communications Error	
CubeWheel 3 Communications Error	
CubeStar Communications Error	
Magnetometer Range Error	
Sun Sensor Overcurrent Detected	
Sun Sensor Busy Error	
Sun Sensor Detection Error	
Sun Sensor Range Error	
Nadir Sensor Overcurrent Detected	Error
Nadir Sensor Busy Error	
Nadir Sensor Detection Error	
Nadir Sensor Range Error	
Rate Sensor Range Error	
Wheel Speed Range Error	
Coarse Sun Sensor Error	
CubeStar Matching Error	
CubeStar Overcurrent Detected	
Orbit Parameters are Invalid	
Configuration is Invalid	
Control Mode Change is not allowed	
Estimator Change is not allowed	
Modelled and measured magnetic field differs in size	
Node Recovery Error	

3 Initial angular rate estimation

The initial angular rate is determined by Kalman filtering of magnetometer data. The MEMS angular rate sensors serves as backup and as verification of the Kalman filter output.

The Rate-Kalman-Filter (RKF) is enabled by setting the *ADCS Run Mode* to *Enabled* (TC ID 10) and the *Estimation Mode* in the *Set Attitude Estimation Mode* telecommand (TC ID 14) to 2 (Magnetometer rate filter).

For the above commands to be accepted, the Signal microcontroller on CubeControl must be switched on first, so that magnetometer data can be sampled. In order to obtain rate sensor telemetry, the Motor microcontroller on CubeControl also has to be switched on. The

CubeControl Signal and/or Motor microcontrollers have to be enabled using an explicit *Power Control* telecommand (TC ID 11).

Once the Motor controller has been powered on the rate sensor measurements can be read using TLM request ID 155. The RKF estimated rates can be read using TLM request ID 147.

The RKF should converge fairly quickly (< 15 seconds). A single pass duration should be long enough to verify the estimated rates, by comparing XYZ-rate sensors telemetry with the estimated rates. Comparison with sampled magnetometer measurements can also aid the confidence. The sampled magnetometer measurements should vary with the same period as indicated by the estimated rates.

Table 4 Initial rate estimation

Command sequence	**Command**	**Parameters**
	ADCS Run Mode (TC 10)	State = Enabled (1)
	Power Control (TC 11)	CubeControl Signal and/or Motor Power = On (1), All others = Off (0)
	Set Estimation Mode (TC 14)	Mode = Magnetometer rate filter (2)
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s
	Rate Sensor Rates (TLM 155)	10s
	Magnetometer Measurement (TLM 151)	10s
Duration	5 mins (nominal case)	
Test condition	XYZ-rate measurement and estimated XYZ-rate is equal (to within 1 deg/s). Magnetometer measurements change with period corresponding to estimated rate.	

An example of estimated and measured Y-rate is shown in the graph below.

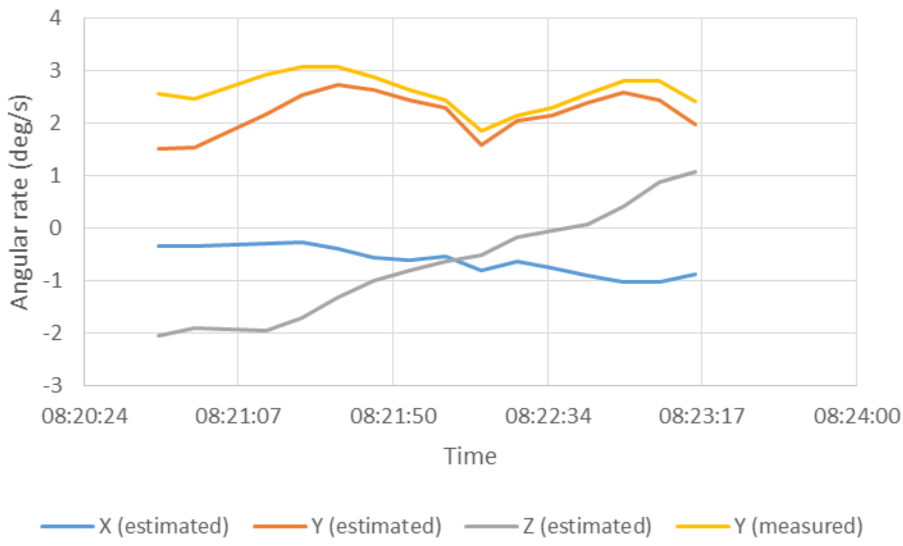


Figure 2 Estimated angular rates and Y-axis measured angular rate example

The corresponding magnetometer measurements (in the body coordinate frame) for this scenario is

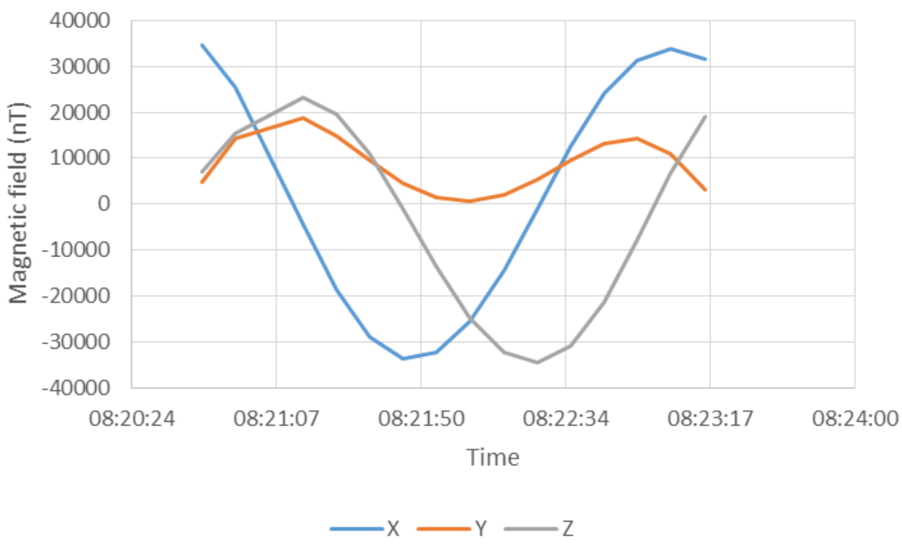


Figure 3 Magnetometer measurements for initial rate estimation

The magnetometer shows large variations in X and Z components which indicates a predominantly Y-spin. The period of the X and Z sinusoidal plots is about 150 seconds, which corresponds to a Y-spin rate of 2.4 deg/s. Further, the fact that the Z sine plot lags behind the X by 90 degrees indicates that it is a positive spin about the Y axis.

3.1 Rate estimation troubleshooting

If the XYZ-axis MEMS rate sensors and estimated rate vector shows disagreement, the cause could be one of the following:

3.1.1 Faulty magnetometer

If the magnetometer develops a fault, the sampled magnetic field signal will show some indication. Possible one or more channels will have a constant output instead of varying with time.

The magnetic field can be sampled by either the Signal or Motor microcontroller on the CubeControl board. It may still be possible to obtain a valid measurement from the Motor microcontroller if the measurement via the Signal microcontroller has been compromised. The default is to sample the magnetometer through the Signal microcontroller, but this behavior can be overridden by powering off the Signal microcontroller and powering on the Motor microcontroller in the *Power Control* telecommand (TC ID 11).

3.1.2 The magnetometer calibration is incorrect or inaccurate

If the magnetometer mounting is incorrectly specified the X, Y and Z estimated rates will be interchanged. In this case, one of the estimated vector components should match the rate sensor measurement (but could have opposite sign). It could also be that the scale matrix or offset vector was incorrectly entered when programming the ADCS configuration.

The problem can be corrected by updating the magnetometer offset and scaling configuration (TC ID 34).

3.1.3 The satellite is spinning too fast

The RKF estimator is only accurate if the satellite is spinning below 35 deg/s. If any component of the rate vector is larger than this, the estimated rate from the RKF will be inaccurate. The MEMS rate sensors will measure accurately to about +/- 75 deg/s in its default configuration. If the satellite is spinning faster than this, the output of the MEMS sensor will saturate (at either +85 or -85 deg/s) and the MEMS rate range can be reconfigured using the *Rate Gyro Configuration* telecommand (TC ID 36) to a higher measurement range. The valid ranges for the *RateSensorMult* parameter is 1 (±75 deg/s) the default, 2 (±150 deg/s), 4 (±300 deg/s) and 12 (±900 deg/s).

If the satellite is spinning at high rates (the absolute angular rate vector norm higher than 35 deg/s), it is still possible to proceed to the detumbling step. But, in this case it will be better to make use of the MEMS rate sensor estimation mode (Mode 1 of TC ID 14) and it may also be necessary to enable the fast detumbling controller first (see next section).

4 Detumbling

Detumbling mode is initiated by sending a *Set Attitude Control Mode* command (TC ID 13) with the *Control Mode* parameter to *Detumbling* (Mode 1). If the magnetometer rate estimator or MEMS rate sensing was enabled before (from the previous step), then it will be acceptable to immediately go to *Y-Thomson* control (Mode 2). The *Detumbling* control will damp the X and Z body rates and this controller can be enabled without any rate knowledge. But, before the *Y-Thomson* controller can be enabled, it will be necessary to delay for a period, until the RKF estimator converges, as this controller will control the estimated Y body rate to a reference value (typically about -1 deg/s).

The first time that *Detumbling* and/or *Y-Thomson* control are attempted, the *Timeout* parameter of the *Set Control Mode* command should be set to 600 seconds. This is to limit the detumbling activation period with wrong torquer polarity, to prevent accidental spin-up due to incorrect torquer settings in the ADCS configuration. At the next pass following the *Detumbling* and/or *Y-Thomson* activation, the angular rates should again be assessed to determine if the magnetic controllers are working correctly. To aid in this assessment, the MEMS rate sensor measurements can be logged alongside the estimated rates. As before, it is necessary to explicitly switch on the Motor microcontroller to enable sampling of the MEMS rate sensors.

Table 5 Detumbling

Command sequence	**Command**	**Parameters**
	ADCS Run Mode (TC 10)	State = Enabled (1)
	Power Control (TC 11)	CubeControl Signal and/or Motor Power = On (1), All others = Off (0)
	Set Estimation Mode (TC 14)	Mode = Magnetometer rate filter (2) or MEMS rate sensing (1)
	Delay	1 min
	Set Control Mode (TC 13)	Initial activation 1: 1) Mode = Detumbling (1) Timeout = 600s Initial activation 2: 2) Mode = Y-Thomson (2) Timeout = 600s Final activation: 3) Mode = Y-Thomson (2) Timeout = 0s
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s
	Rate Sensor Rates (TLM 155)	10s

	Magnetometer Measurement (TLM 151)	10s
	Magnetorquer commands (TLM 157)	10s
Duration	Initial activations: 1 orbit Final activation: until Y-Thomson spin achieved	
Test condition	Initial activations: Decrease in X and Z rates and Y rate changing towards reference spin rate Final activation: Until steady-state Y-Thomson has been reached (X and Z rates around 0 deg/s, Y-rate at reference value of -1 deg/s).	

The expected angular rate telemetry for a steady-state Y-Thomson spin is shown in the following graph. The Y-spin reference was set at -2.2 deg/s for the QB50 P1 & P2 satellites.

NB: To achieve a stable Y-Thomson spin the body Y-axis moment of inertia (MOI) needs to be the largest by about 5% above the middle MOI. This has to be ensured through a proper mechanical design and if it cannot be achieved easily by proper placement of the satellite components, extra mass must be added: For example, if $I_{ZZ} > I_{YY}$ extra mass must be added symmetric to the satellite CoM, but close to the body Z-axis and as far as possible from the satellite body Y-axis to ensure I_{YY} exceeds I_{ZZ} by more than 5%.

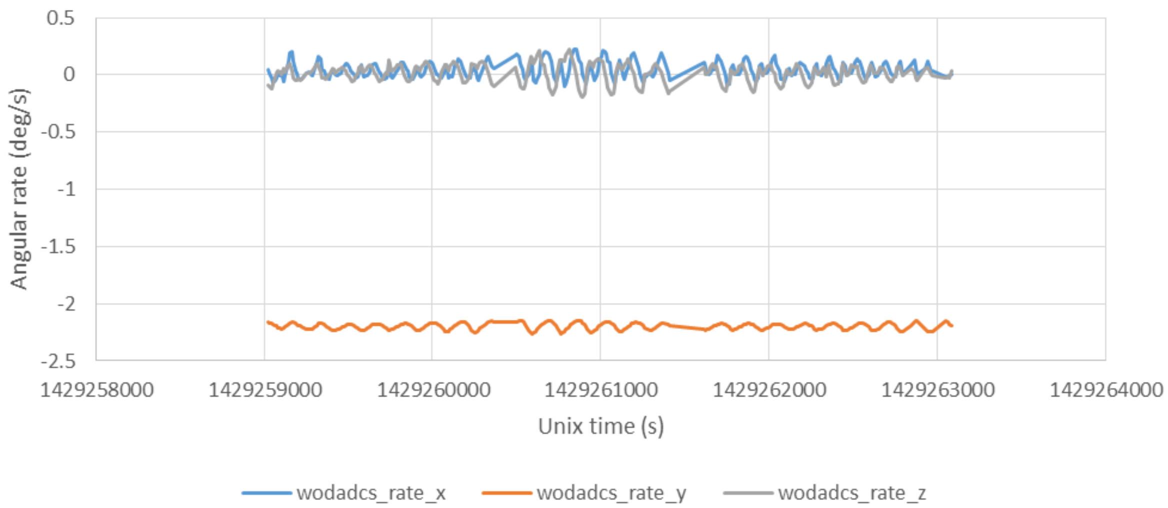


Figure 4 Example Y-Thomson spin state - angular rates

Y-Thomson motion also requires that the spin axis is aligned with the orbit normal. This can be determined from the sampled magnetic field vector. For a Y-spin, the magnetic field will vary sinusoidally in the X and Z components with a smaller slow varying Y-component. The graph below shows that the satellite motion is converging to such a state, but the Y-component of the magnetic field vector is still too large for a polar orbit (small component normal to the orbit plane, i.e. Y-component measurement) so more time is needed to settle into an accurate Y-Thomson state.

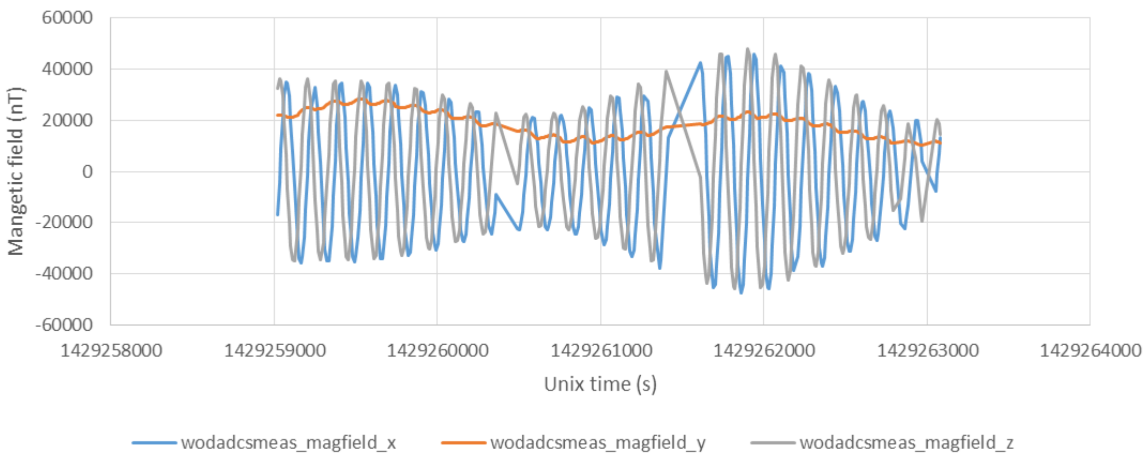


Figure 5 Example Y-Thomson spin state - magnetic field vector

4.1 Detumbling from high initial rates

The normal detumbling control cannot be used at high initial tumbling rates. At rates above 30 deg/s the normal detumbling control will cause the satellite rates to increase instead of decrease. This comes as a result of the latency between the time the magnetic field is sampled and when the torque is applied through the torquer rods. The ADCS loop operates at a fixed period of 1s and this limits the maximum angular rate for which normal detumbling control is effective.

It is, however, possible to recover from angular rates above this by using the *Fast Spin Detumbling* (Mode = 9 of TC ID 13). This magnetic controller will detumble from all rate magnitudes below 100 deg/s, see Figure 6 below for a simulation result of a 3U CubeSat. If the angular rates above 100 deg/s a 10 Hz sampling detumble controller implement directly in CubeControl's Signal processor can be activated by using the *Very Fast Spin Detumbling* (Mode = 8 of TC ID 13). This fast magnetic controller should be able to detumble from an initial rate magnitude as high as 1000 deg/s.

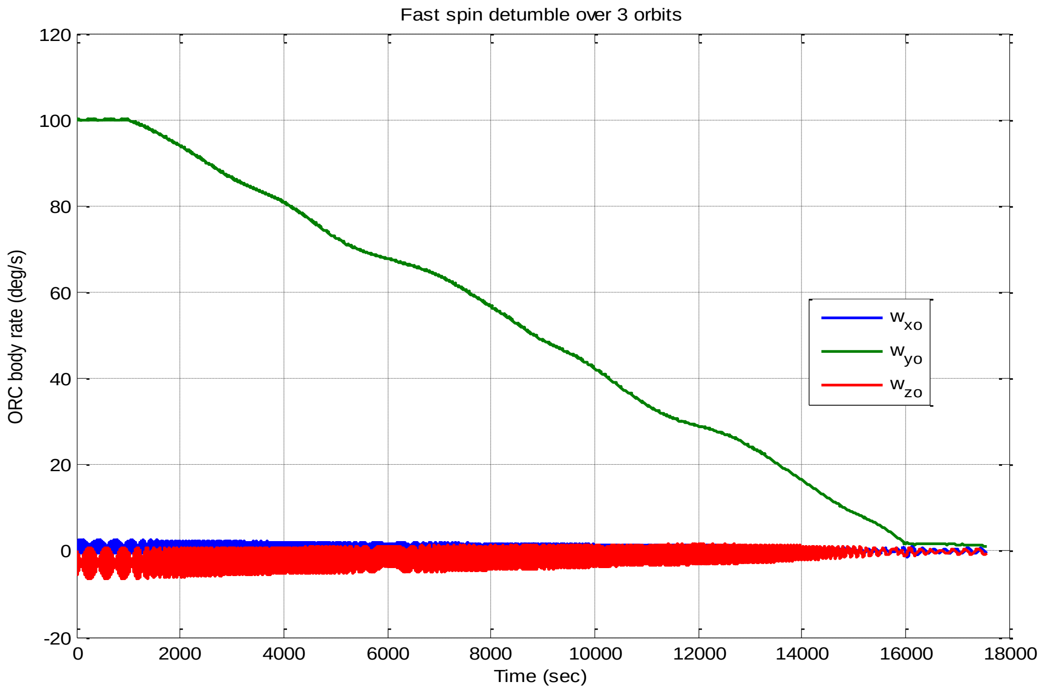


Figure 6: Example of high initial rate detumbling

4.2 Detumbling troubleshooting

Ineffective or undesired detumbling performance could be caused by incorrect magnetometer calibration/mounting or incorrect torquer configuration. Both these causes contribute to the same problem, since it results in a torquer firing to achieve an outcome based on mismatched magnetic field vector.

If the estimated rates are within the controllable range of normal detumbling, the default torquer configuration will be correct as verified on the ground (typically torquer1 = +X, torquer2 = +Y, torquer3 = +Z, but this can be different for non-standard mounting of CubeADCS unit). The default torquer configuration and polarity must be tested thoroughly for correctness in the satellite body axes, after delivery of the ADCS unit. If any problems remain, the magnetometer calibration and mounting should then be corrected.

If the default torquer configuration is being used, and the magnetometer calibration is known to be correct and detumbling performance is still poor or ineffective, one should consider the possibility that the magnetometer boom has deployed out of its own accord (see the next section for commanded magnetometer boom deployment). Try to set the magnetometer mounting angles to that of the deployed magnetometer and repeat the detumbling attempt.

5 Magnetometer deployment

Deployment of the magnetometer is required to limit the magnetic disturbances caused by the satellite bus, e.g. currents flowing in solar panels, wire loops and reaction wheel magnets. Deployment should occur while ground contact with the satellite has been established (during a ground station overpass). Real-time magnetometer measurements at 1 second is required to evaluate if the deployment was successful. It is also better that the satellite is still in a slow tumble (e.g. Y-Thomson spin), otherwise the magnetometer deployment might be difficult to observe through analysis of the magnetometer channel measurements.

The control mode should be set to none (no control must be taking place).

Table 6: Magnetometer boom deployment

Prerequisites	Satellite in Y-Thomson spin	
Command sequence	**Command**	**Parameters**
	ADCS Run Mode (TC 10)	State = Enabled (1)
	Power Control (TC 11)	CubeControl Signal and Motor Power = On (1), All others = Off (0)
	Set Estimation Mode (TC 14)	Mode = Magnetometer rate estimator (2)
	Set Control Mode (TC 13)	Mode = None (0)
	Deploy Magnetometer Boom (TC 7)	First attempt: Timeout = 2s Second attempt: Timeout = 5s Third attempt: Timeout = 10s
	Set Magnetometer Mounting Configuration (TC 33)	Deployed magnetometer angles
	Save Configuration (TC 63)	
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	1s
	Estimated Angular Rates (TLM 147)	1s
	Rate Sensor Rates (TLM 155)	1s
	RAW Magnetometer Measurement (TLM 170)	1s
	CubeControl Current (TLM 172)	1s
Duration	1 min	
Test condition	Observe step change in RAW magnetometer measurements	

Both the Signal and Motor microcontrollers have to be enabled by explicit *Power Control* command. The first deployment attempt can use a timeout of 2s. If the deployment was not observed, longer activations of 5s and 10s can be attempted.

The magnetometer deployment event will show up as a step change in the RAW magnetometer measurements. The magnetometer should be sampled at 1s intervals. The estimated angular rates will also show an exchange between two of the X, Y and Z components as a result of successful deployment, the third axis around which the magnetometer deployment took place, should show no change in estimated angular rate.

The current telemetry will also be instrumental to show if deployment was actually attempted (1 sec sampling of the *VBat Current* telemetry channel in *CubeControl currents* TLM ID 172).

After successful deployment, it will be necessary to update the magnetometer configuration to reflect the new mounting angles. This is performed by sending a *Set Magnetometer Configuration* telecommand (TC ID 33) with the updated mounting angles. The latter command will only set the configuration temporarily. If the updated configuration has been verified (after deployment, the estimated angular Y-rate might no longer corresponds to the MEMS sensor measurement. But after setting the updated mounting angles, these components should be the same again), the changes can be made permanent by sending a *Save Configuration* command (TC ID 63).

If the magnetometer deployment could not be observed, it is possible that the deployment failed, or that deployment already occurred previously. In both cases, users should continue onto the next step.

6 Magnetometer Calibration

The magnetometer calibration that is done on ground, prior to delivery of the ADCS unit, can be improved on by a procedure that involves sampling the magnetic field vector over one orbit, and post-processing of the logged data. The satellite does not have to be controlled in this period, but it should ideally be doing a slow tumble (< |3 deg/s|), i.e. be in a Y-Thomson state.

The calibrated measured magnetic field vector should be sampled at a period of 10s for at least one full orbit (more data can also be used).

The sampled magnetometer data is then processed by making use of a batch linear least-squares method to find the bias and orthogonality (sensitivity) matrix. The calibration processing is incorporated in the CubeSupport utility [R02]. References on the procedure can be found in

- John L. Crassidis, Kok-Lam Lai, and Richard R. Harman. "Real-Time Attitude-Independent Three-Axis Magnetometer Calibration", Journal of Guidance, Control, and Dynamics, Vol. 28, No. 1 (2005), pp. 115-120.

- Roberto Alonso, Malcolm D. Shuster, TWOSTEP, a Fast Robust Algorithm for Attitude-Independent Magnetometer Bias Determination, The Journal of the Astronautical Sciences, Vol. 50, No. 4. (December 2002), pp. 433-451

It is also important to know the accurate position of the satellite at the times the samples were taken. An SGP4 orbit propagator is used by the CubeSupport calibration utility and the closest TLE to the sampled data should be used. (The time at which samples were taken should be accurately known).

The calibration utility will also output the RMS error between measured and modelled magnetic field vector, giving an indication of the measurement accuracy of the magnetometer.

Once updated magnetometer offset and sensitivity matrix parameters have been computed, it can be programmed onto the ADCS by first sending a *Set Magnetometer Configuration* (TC ID 34 & 35) command, followed by a *Save Configuration* (TC ID 63) command to store it permanently in flash memory.

Table 7: Magnetometer calibration

Prerequisites	All angular rate vector components in range -3 to +3 deg/s	
Command sequence	**Command**	**Parameters**
	ADCS Run Mode (TC 10)	State = Enabled (1)
	Power Control (TC 11)	CubeControl Signal and Motor Power = On (1), All others = Off (0)
	Set Estimation Mode (TC 14)	Mode = Magnetometer rate estimator (2)
	Set Control Mode (TC 13)	Preferred Mode = Detumbling (2)
	Delay	1 Orbit
	On-ground processing	
	Set Magnetometer Configuration (TC 34 & TC 35)	Updated sensitivity matrix and offset vector
	Save Configuration (TC 63)	
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s
	Rate Sensor Rates (TLM 155)	10s
	Calibrated Magnetometer Measurement (TLM 151)	10s
Duration	1 orbit (logging)	
Test condition	Magnetometer measurement error has been determined	

7 Angular rate and pitch angle estimation

Towards activation of Y-momentum mode, it is first necessary to verify the momentum wheel operation, and to do so knowledge of the pitch attitude angle is needed. The *Magnetometer rate filter with pitch estimation* (Estimation Mode 3) will estimate the angular rates and pitch angle from magnetometer measurements.

The mode should be used once the satellite is already in a Y-Thomson spin, and the normal detumbling control should continue to be used. Attitude rates and attitude angles should be logged at 10s intervals for one orbit.

At the end of the orbit it should be verified that the satellite is still in a Y-Thomson spin and that the estimated pitch angle changes at the reference spin rate.

Table 8: Angular rate and pitch angle estimation

Prerequisites	Y-Thomson spin state, held for at least 1 orbit	
Command sequence	**Command**	**Parameters**
	ADCS Run Mode (TC 10)	State = Enabled (1)
	Power Control (TC 11)	CubeControl Signal and Motor Power = On (1), All others = Off (0)
	Set Estimation Mode (TC 14)	Mode = Magnetometer rate filter with pitch estimation (3)
	Set Control Mode (TC 13)	Mode = Detumbling (2)
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s
	Estimated Attitude Angles (TLM 146)	10s
	Rate Sensor Rates (TLM 155)	10s
	Magnetometer Measurement (TLM 151)	10s
Duration	1 orbit (logging)	
Test condition	Satellite remains in Y-Thomson spin, pitch angle observed to change at reference spin rate	

8 Y-wheel ramp-up test

Before enabling the Y-momentum mode, it has to be verified that the momentum wheel can be commanded and that its angular momentum has the correct sign.

The wheel ramp-up test is carried out while the satellite is already in a Y-Thomson spin. The Magnetometer rate filter with pitch estimation mode should be active before commanding the wheel, so that the effect in angular rates and pitch angle can be observed. The test is carried out with the satellite in view of the ground station.

Since the pitch estimation makes use of the IGRF model and must know the satellite position, it will be necessary to set the orbit parameters to recent TLEs provided by NORAD on www.space-track.org or www.celestrak.com . For accurate satellite position and velocity prediction, it is also important that the on-board time is synchronized to the current Unix time.

To begin, the CubeControl Motor microcontroller and Y-Wheel (depending on the wheel configuration CubeWheel-1, -2 or -3) should be enabled by explicit telecommand. The detumbling controller that should be active (to maintain the Y-Thomson spin) should be deactivated temporarily by setting the control mode to None.

The wheel will now be commanded to a constant value, so as to absorb the spinning satellite angular momentum. The Y-wheel speed should be set to the following reference value

$$\omega_{wheeltest}\,[\mathrm{RPM}] = I_{yy}\omega_{y-ref} \times 83\,333$$

Where I_{yy} is the satellite moment of inertia about the Y-body axis (passing through the centre of mass) in kg.m^2 units, ω_{y-ref} is the reference spin rate in deg/s for the detumbling controller (default value is -1 deg/s). As an example, if a 3U CubeSat has I_{yy} = 5.0 x 10^{-2} kg.m^2, and reference spin rate of -1 deg/s. A wheel speed command of -4167 RPM is needed to absorb all the satellite angular momentum into the wheel.

The wheel is then allowed to spin at constant speed for a period of 2 minutes. During this time the measured wheel speed, estimated angular rates, measured Y-rate and estimated pitch angle is logged at 1s period. After the 2-minute delay period, the wheel is commanded to stop (speed command = 0) and the detumbling controller is activated again to maintain the Y-Thomson spin state.

Table 9: Y-wheel ramp-up test

Prerequisites	Magnetometer rate filter with pitch estimation mode has been active for 1 min. Y-Thomson spin state held for at least 1 orbit prior to this	
Command sequence	**Command**	**Parameters**
	ADCS Run Mode (TC 10)	State = Enabled (1)
	Power Control (TC 11)	CubeControl Signal, Motor Power and CubeWheel-i = On (1) {where, i = 1/2/3 i.e. the Y-Wheel} All others = Off (0)
	Set Estimation Mode (TC 14)	Mode = Magnetometer rate filter with pitch estimation (3)
	Set Control Mode (TC 13)	Mode = None (0)
	Wheel speed command (TC 17)	Commanded Y Speed = $\omega_{wheeltest}$ [RPM]

Telemetry logging	Delay	2 min
	Wheel speed command (TC 17)	Commanded Y Speed = 0 RPM
	Set Control Mode (TC 13)	Mode = Detumbling (2)
	Telemetry frame	**Period**
	Current Unix time (TLM 140)	1s
	Estimated Angular Rates (TLM 147)	1s
	Estimated Attitude Angles (TLM 146)	1s
	Rate Sensor Rates (TLM 155)	1s
	Measured wheel speed (TLM 156)	1s
	Magnetometer Measurement (TLM 151)	1s
Duration	1 pass	
Test condition	• Observe measured wheel speed match the commanded speed. • Observe the satellite estimated angular Y-rate go to zero when the wheel ramps up, and go back to reference spin rate when wheel is stopped. • Observe pitch angle change to near-constant (or slowly varying) when wheel is spinning.	

The outcome of the wheel ramp-up test should be to check that the wheel actually achieves the commanded wheel speed. As a result, the satellite should stop spinning about the Y-axis, since all the angular momentum will be absorbed by the spinning wheel. When the wheel stops spinning, the momentum is transferred back to the satellite, and it will continue in a Y-Thomson motion.

9 Y-momentum mode commissioning

The procedure that is described below in Table 10 for Y-momentum activation is suggested for initial commissioning attempts. The procedure involves first making use of the magnetometer rate filter and pitch estimator in the beginning of Y-momentum activation, and after the controller settles the Full State EKF estimation mode is enabled, making use of only magnetometer measurements.

This is the procedure that was successfully employed on the precursor satellites in the presence of disturbance torques. As teams gain more experience in operation of the ADCS and satellite, and as the CubeSense sun and nadir sensors are tested, it could be possible to shorten the sequence below.

Since Y-momentum mode makes use of the pitch estimation or the EKF estimation mode, it will be necessary to set the orbit parameters to recent TLEs provided by NORAD on www.space-track.org or www.celestrak.com . For accurate satellite position and velocity prediction it is also important that the on-board time is synchronized to current Unix time. The on-board calculated position and velocity should be logged (at least for the first activation) to make sure that orbit parameters are reliably uploaded.

For initial activations, before the sun and nadir sensor has been commissioned, only magnetometer measurements will be used in the EKF. It is necessary to disable the use of the CSS, Sun and Nadir sensor in the Full State EKF by sending a *Set Estimation Parameters 2* telecommand (TC ID 44) with Mask parameters set to *false*. The remaining parameters in the *Set Estimation Parameters 2* (TC ID 44) command should be set to default values as in [R01].

Once this initial setup has been completed, the estimation mode is first set to Magnetometer rate filter with pitch estimation (Mode 3), followed by the command to enable Y-momentum control mode. The first time this is attempted, the control timeout can be limited to 20 minutes, for initial verification. Subsequent activations can set the timeout to infinite.

Once it has been observed that the pitch angle settles close to zero, the Full State EKF (Mode 5) can be enabled.

Table 10: Y-momentum mode activation

Prerequisites	Magnetometer rate filter with pitch estimation mode has been active for 1 min. Y-Thomson spin state held for at least 1 orbit prior to this	
Command sequence	**Command**	**Parameters**
	ADCS Run Mode (TC 10)	State = Enabled (1)
	Set Unix time (TC 2)	Current Unix time
	Set Orbit Parameters (TC 45)	Current TLEs
	Save Orbit Parameters (TC 64)	Save to Flash memory
	Set Estimation Parameters 2 (TC 44)	Mask Sun sensor = 0 (false) Mask Nadir sensor = 0 (false) Mask CSS = 0 (false) All others = defaults
	Set Estimation Mode (TC 14)	Mode = Magnetometer rate filter with pitch estimation (3)
	Set Control Mode (TC 13)	Mode = Y-momentum (3) First activation: Timeout = 20mins Subsequent activation: Timeout = 0s (infinite)
	Delay until pitch angle is between -10 to +10 deg	
	Set Estimation Mode (TC 14)	Mode = Full State EKF (5)
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s
	Estimated Attitude Angles	10s

	(TLM 146)	
	Rate Sensor Rates (TLM 155)	10s
	Measured wheel speed (TLM 156)	10s
	Magnetometer Measurement (TLM 151)	10s
	Satellite position (LLH) (TLM 150)	10s
Duration	Initial activation: 20 mins Subsequent activation – indefinitely	
Test condition	• Pitch angle is controlled to zero • Angular rates are controlled to zero • Wheel momentum stays around reference value	

One such activation for QB50P1 is shown in the following plots (Figs. 7-9). The Y-momentum controller was enabled for 10 minutes, after which the control timeout was reached and no control was performed after that. It can be seen that the pitch angle is controlled to zero, and the Y-angular rate also went to 0 deg/s. At the end of the activation the wheel stopped spinning and the satellite went back into a Y-Thomson spin.

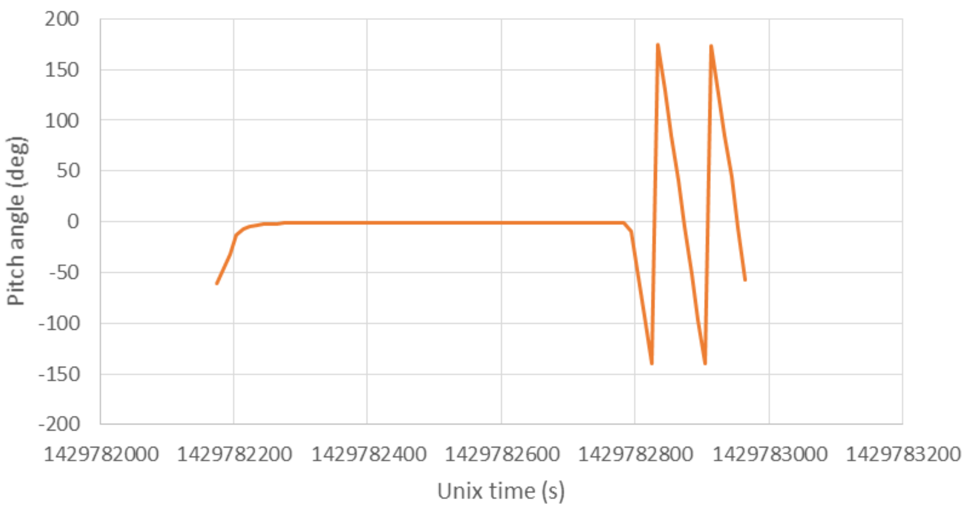


Figure 7: Pitch angle for initial Y-momentum activation

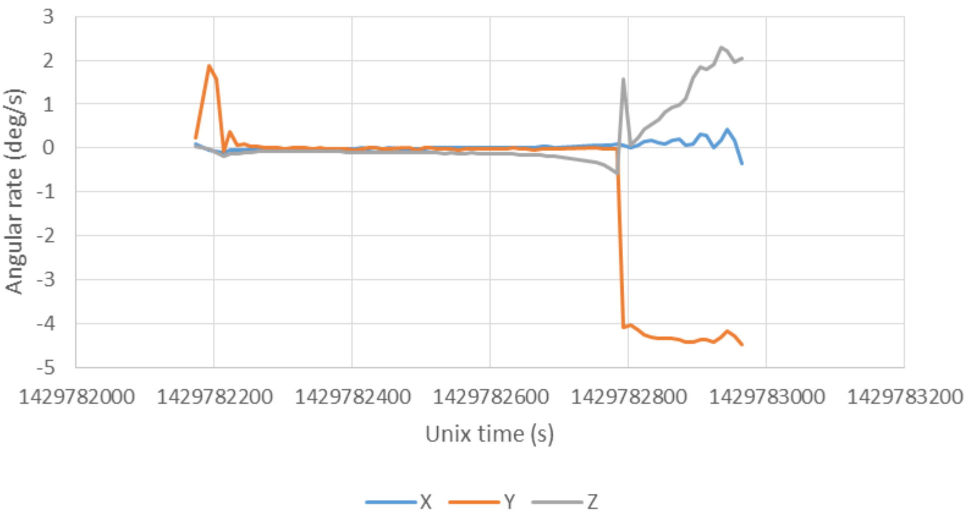


Figure 8: Angular rates for initial Y-momentum activation

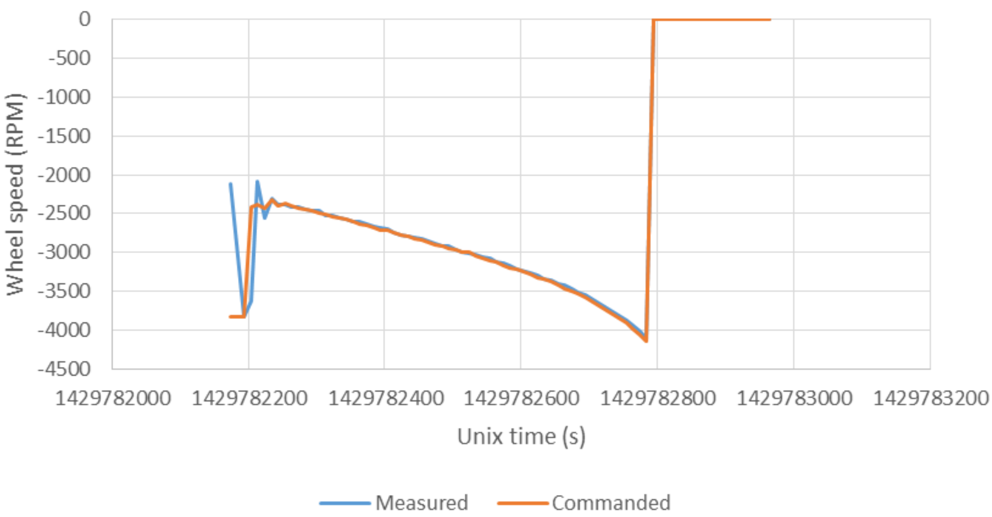


Figure 9: Commanded and measured wheel speed for initial Y-momentum activation

It can be seen from the last plot that the wheel speed did not remain constant (or near-constant) around the reference value as it was intended. This is because of an external disturbance torque that wants to rotate the satellite away from nominal zero roll, pitch and yaw attitude. The wheel controller counteracts the disturbance and keeps the satellite stable, but it results in momentum build-up on the wheel.

In this case the performance can be improved by increasing the gain for the magnetic momentum management controller (see next sub-section). It was also found that switching to EKF is necessary (the plots above were obtained for the magnetometer rate filter with pitch angle estimator) because the external disturbance also causes deviations in the roll and yaw angles, which decreases the pitch estimation accuracy.

It is likely that it will be necessary to adjust gain values and estimation parameters, which is why logging is essential at this stage. Gain values, estimation modes and estimation settings can be adjusted based on observation, but simulation testing is also strongly advised. The next section shows some simulation results of detumbling, Y-Thomson and finally Y-Momentum mode.

9.1 Typical simulation results

The orbit used during this simulation tests is a 500 km circular sun-synchronous orbit. The orbit elements used are presented in Table 11. The simulation was executed using a sample period of 1 second for all models, controllers and estimators.

A SGP4 model was used to simulate the satellite's orbit in combination with an accurate sun orbit model. The geomagnetic field was simulated using a 10^{th} order IGRF spherical harmonic model. The aerodynamic drag and solar radiation disturbance forces were modelled, taking into account the properties and attitude of the 3U CubeSat body, relative to the atmospheric velocity and the sun vector directions respectively.

Table 11: Orbit used for 3U CubeSat simulation testing

Orbit Parameter	Value
Semi-major axis	6878 km
Initial Inclination	97.26º
Orbital Period	5676 sec
Eccentricity	0.0003
Sun-synchronicity	LTDN 09h00

All the CubeADCS sensors were modelled with realistic measurement noise and slow varying offset errors where applicable. All the CubeADCS actuators were modelled with their saturation and quantisation limits. The remainder of this section will present the simulation results graphically from typical initial conditions for the various control modes from detumbling to Y-momentum wheel control.

<u>*Control Modes 1 & 2:*</u>

Detumbling using a *Bdot* and *Y-spin* controller and MEMS rate sensor for direct measurement of the body Y_B angular rate. The initial roll, pitch and yaw angles are -5^0, 20^0 and 5^0 respectively. The initial angular rate vector (orbit referenced) is: $\boldsymbol{\omega}_{B/O} = \begin{bmatrix} 0.3 & -1 & -0.3 \end{bmatrix}^T$ ^{0}/sec. Figures 10 and 11 show the detumble until Y-momentum wheel stabilisation results. Figure 10 shows how the X_B and Z_B inertially referenced body rates are quickly dumped after the first orbit (starting at 5676 sec). The Y_B body rate is controlled to the reference rate of -2.2 ^{0}/sec.

<u>*Control Modes 3 & 4:*</u>

At the start of the second orbit (11352 sec), the *Y-momentum wheel* controller and a nutation damping and Y-momentum management magnetic control are enabled, to 3-axis stabilise the attitude angles to zero values (see Figure 11) and control the Y-wheel momentum to -1 milli-Nms. Pitch attitude maneuvers to $+90^0$ and -90^0 can also be seen during the forth orbit (starting at 17028 sec).

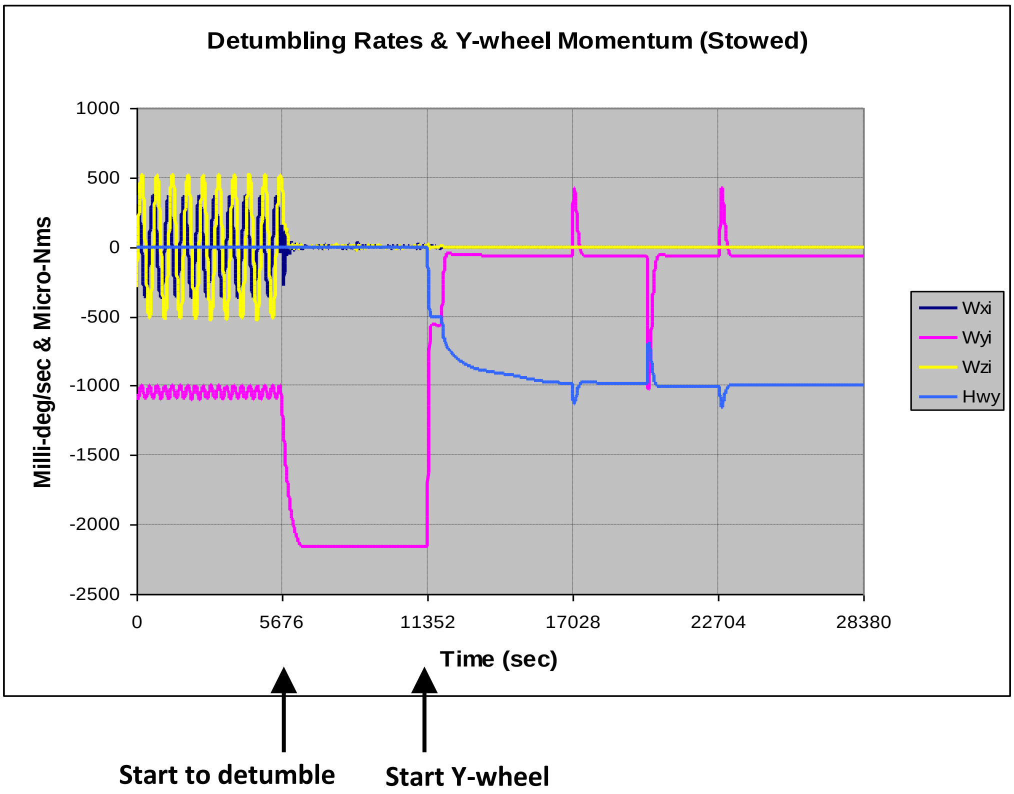


Figure 10: Detumble and Y-momentum wheel rates from Y-Thomson to Y-momentum control

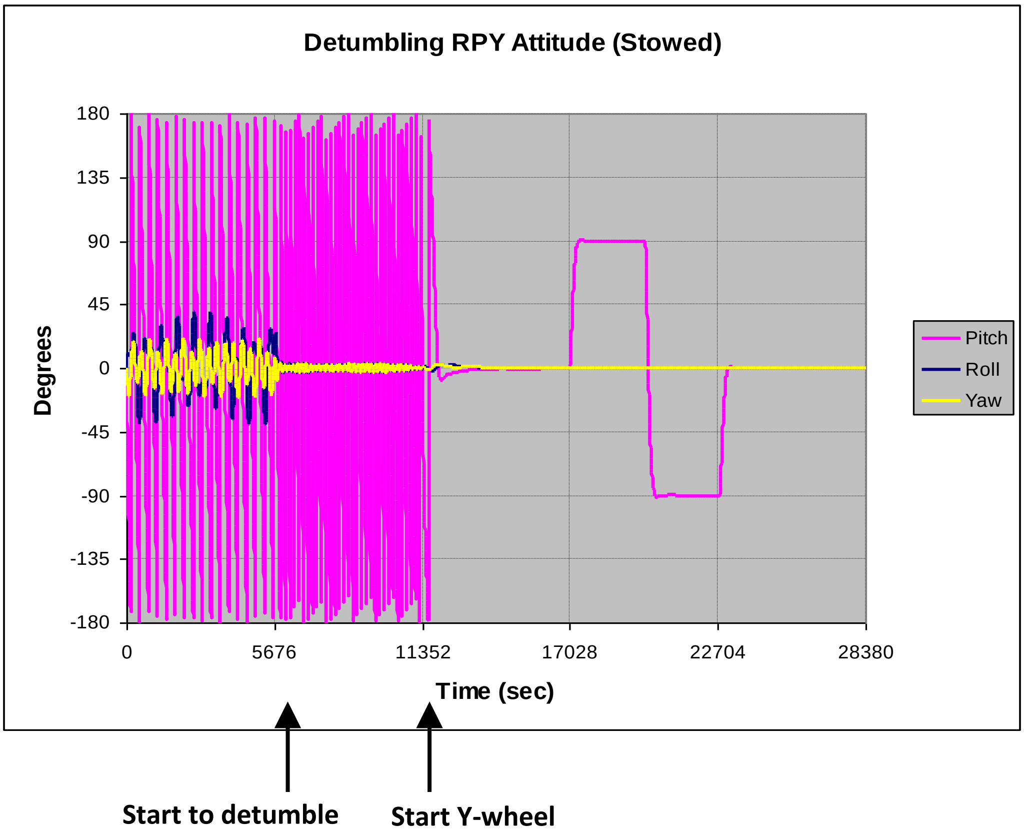


Figure 11: Attitude angles from Y-Thomson to Y-momentum control

9.2 Adjustments for Y-momentum mode

The following adjustments can be made in the ADCS configuration to improve on the Y-momentum performance.

9.2.1 Estimation modes & other sensors

Estimation accuracy can be improved by

- Using the Full State EKF together with Y-momentum control mode
- Incorporating Sun and/or Nadir sensor measurements in the EKF
- Calibrating the magnetometer
- Incorporating the Star Tracker (CubeStar) measurements in the EKF
- Using the gyro-based EKF

Magnetometer calibration was described in Section 6. Testing the sun and nadir sensor is required before selecting them for use in the EKF. The test is described in the following section.

It is also possible to adjust the system noise and measurement noise covariance used by the Full State EKF to further improve convergence.

Note, the CSS is considered unreliable if not all 6 photodiodes (one per body facet, with an unobstucted hemispherical FoV) can be accommodated. The strategy followed on the precursor QB50 satellites of using 5 photodiodes and estimating the missing facet has been shown to have poor accuracy. The CSS vector that is obtained in this way must not be used in an EKF, the latest ADCS code will not use the CSS vector in the EKF (even if the CSS mask is enabled, i.e. set to 1 or *true*).

9.2.2 Y-Wheel controller gains

The prelaunch simulation selected wheel controller proportional and derivative gains have been proven correct during the QB50 precursor commissioning. In different dynamic situations, such as in the presence of high aerodynamic torque (e.g. as expected during the low altitude final QB50 mission), different gains have to be used.

9.2.3 Y-Wheel reference momentum

If there are large external disturbance torques, one can consider increasing the reference wheel momentum to provide more gyroscopic stiffness and lessen the effect of disturbance torques.

9.2.4 Y-Momentum management gain

If Y-momentum build-up is observed (as in the example above), then increasing the magnetic momentum dumping gain can help to reduce the build-up. It may also be possible to fly at a different non-zero pitch angle to reduce the Y-axis aerodynamic disturbance torque. A realistic simulation test with full aerodynamic modelling may give an indication if such an angle exists.

10 Sun/Nadir sensor commissioning

The CubeSense Sun and Nadir sensor is tested by first obtaining a log of measurements over at least 1 orbit. This should take place while the satellite is already in a stable nadir pointing attitude using the Y-momentum control mode. Getting the satellite into such a state was discussed in the previous sections.

It is important that the Sun and Nadir sensors remain masked off (Mask = 0 or *false*) initially – so that even when they are sampled, the measurements are not used in the EKF. Only if they have been verified their masks can be set true for use in the EKF.

Table 12: Sun and Nadir sensor test

Prerequisites	Satellite in Y-momentum control with stable attitude	
Command sequence	**Command**	**Parameters**
	Power Control (TC ID 11)	CubeSense Power = On (1) All others = Default
	Set Estimation Parameters 2 (TC 44)	Mask Sun sensor = 0 (false) Mask Nadir sensor = 0 (false) All others = defaults
	Set Estimation Mode (TC 14)	Mode = Full State or Gyro EKF (5 or 6)
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s
	Estimated Attitude Angles (TLM 146)	10s
	Rate Sensor Rates (TLM 155)	10s
	Raw CSS measurements (TLM 168 and if needed 169)	10s
	Raw Nadir sensor measurements (TLM 166)	10s
	Raw Sun sensor measurements (TLM 167)	10s
Duration	One orbit	
Test condition	Raw Nadir measurement - X and Y angles close to zero - Zero or few detection errors in sunlit - Invalid detection result in eclipse Raw sun measurement - X and Y varying to correspond with CSS measurements. - Zero or few detection errors in sunlit - Invalid detection result in eclipse	

The Nadir sensor output should show a resulting vector close to $[0, 0, 1]^T$, since the satellite should be mostly nadir pointed throughout. The sun sensor raw measurements should correlate with CSS measurements. Both Sun and Nadir raw measurements should report invalid detection results in eclipse.

Once the sensors have been verified, they can be enabled for inclusion in the Full State EKF by sending a *Set Estimation Parameters 2* telecommand (TC ID 44) with Mask parameters set to *true*. The remaining parameters in the *Set Estimation Parameters 2* (TC ID 44) command should be set to default values as in [R01].

10.1 Adjustment to Sun and Nadir sensor parameters

10.1.1 Camera and detection settings

If the Sun or Nadir sensor reports detection error results when it was supposed to report a valid result, it could be because of incorrect camera gain and/or exposure settings. These settings should ideally be adjusted after capturing and downloading images to compare. The *Sun Sensor exposure time* parameter (default = 0) in the *Set sun sensor configuration parameters* telecommand (TC ID 26) can be used to adjust the sun exposure time. The *Nadir Sensor exposure time* parameter (default = 35) in the *Set nadir sensor configuration parameters* telecommand (TC ID 27) can be used to adjust the nadir exposure time.

The sun and nadir detection threshold can also be adjusted accordingly (again, having a downloaded sun and nadir image is the best way to determine what threshold to use). The *Sun detection threshold* parameter (default = 150) in the *Set sun sensor configuration parameters* telecommand (TC ID 26) can be used to adjust the sun threshold. The *Nadir detection threshold* parameter (default = 150) in the *Set nadir sensor configuration parameters* telecommand (TC ID 27) can be used to adjust the nadir threshold.

Sensor boresights are determined prior to delivering the units and should not have to be changed.

10.1.2 Mounting transform

If the raw detection results are valid, but the calibrated sun or nadir vector does not match with expected values, it could be because of incorrect mounting transform. See the CubeADCS Reference Manual [R01] for an example on how to configure/determine the rotation angles for the mounting transform. These mounting angles can be changed with the *Set sun sensor configuration parameters* telecommand (TC ID 26) and the *Set nadir sensor configuration parameters* telecommand (TC ID 27).

10.2 Capture, save and download a CubeSense image

The *Save Image Command* (TC ID 80) can be used to capture and save a CubeSenses camera image in the SD card file system. The *Camera Select* parameter specifies which camera to use, Nadir = 0, Sun = 1. The *Image Size* parameter specifies the resolution of the camera image:

0. 1024 x 1024 pixels (100% resolution)
1. 512 x 512 pixels (50% resolution)
2. 256 x 256 pixels (25% resolution)
3. 128 x 128 pixels (12.5% resolution)
4. 64 x 64 pixels (6.25% resolution)

The image file on the SD card can then be downloaded by the file transfer process described in the CubeADCS Reference Manual [R01]. These images can then be inspected on the ground to ensure that the sun or earth has been correctly captured.

11 CubeStar commissioning

The CubeStar star tracker is tested by first obtaining a log of measurements over at least 1 orbit. This should take place while the satellite is already in a stable nadir pointing attitude using the Y-momentum or 3-axis reaction wheel control mode. Getting the satellite into a Y-momentum state was discussed in the previous sections, the 3-axis reaction wheel control mode will be discussed later.

It is important that CubeStar remain masked off (Mask = 0 or *false*) initially – so that even when it is sampled, the measurements are not used in the EKF. Only if CubeStar has been verified its mask can be set true for use in the EKF.

Table 13: CubeStar test

Prerequisites	Satellite in Y-momentum control with stable attitude	
Command sequence	**Command**	**Parameters**
	Power Control (TC ID 11)	CubeStar Power = On (1) All others = Default
	Set Estimation Parameters 2 (TC 44)	Mask Star tracker sensor = 0 (false) All others = defaults
	Set Estimation Mode (TC 14)	Mode = Full State or Gyro EKF (5 or 6)
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s
	Estimated Attitude Angles (TLM 146)	10s
	Rate Sensor Rates (TLM 155)	10s
	Raw Star Tracker measurements (TLM 211)	10s
Duration	One orbit	
Test condition	Raw star tracker measurements: - Stars detected and stars identified - Star tracker status flags (see Table 14: Star Tracker Status Flags) - Confidence and magnitude of Stars 1-3 - X,Y centroid and catalogue number of Stars 1-3 - Timing results of capture, detection and identification phases	

Table 14: Star Tracker Status Flags

Bit	Name	Description
0	CubeStar initialized and ready	Successful initialization and ready for image capture
1	Image captured success	Successfully captured an image
2	Stars detected success	Successfully detected stars in image
3	Stars identified success	Successfully identified/matched stars in image
4	Main operating loop time error	Star tracker execution loop exceeded 1 second
5	Max stars detected	Exceeds maximum number of stars in FoV
6	Less than three stars in FoV	Not enough stars for successful identification
7	I2C communication error	Encountered an I2C communication error

The star tracker log file must then be downloaded and analysed. When the following *Star Tracker Status* flags are set true,

- *CubeStar initialised and ready* flag = 1
- *Image captured success* flag = 1
- *Stars detected success* flag = 1

Then the *Number Stars Detected* parameter (in TLM ID 211) will vary typically between 3 and 15 stars. In the unlikely event that more than 15 stars were detected the *Max stars detected* flag will be set, this may indicate an incorrect (too low) settings of the *StarTracker detection threshold* and *StarTracker star threshold* parameters that can be adjusted in the *Set Star Tracker Configuration* telecommand TC ID 37 (default values = 22 and 3). It can also potentially indicate an incorrect setting of the *StarTracker exposure time* parameter that can be adjusted in the *Set Star Tracker Configuration* telecommand TC ID 37 (default value = 2704). The detail explanation of these parameters can be found in the CubeStar Reference Manual [R03].

The *Number Star Identify* parameter (in TLM ID 211) will vary typically between 3 and 15 stars (but less or equal to the number of stars detected). In the unlikely event that zeros stars are mostly identified, but enough detected, it can be due to a too small tolerance in the *Star Tracker Error margin* parameter that can be adjusted in the *Set Star Tracker Configuration* telecommand TC ID 37 (default value = 10), see [R03] for a detailed explanation.

Normally 3 stars will be matched successfully with catalogue stars and these star's confidence levels, magnitude, catalogue star number and X & Y centroid values will be made available in the log file from the TLM ID 211 requests. See [R03] for more detail.

Finally the measured execution time values for the capture, detection and identification processes can be inspected, especially if a *Main operating loop time error* is flagged true in the *Star Tracker Status* parameter (TLM ID 211). See [R03] for more detail.

11.1 Adjustment to CubeStar parameters

11.1.1 Camera and detection settings

The *Set Star Tracker Configuration* telecommand (TC ID 37) can be used to change several of the CubeStar detection parameters, the detail can be found in the CubeStar Reference Manual [R03]. Sensor boresights are determined prior to delivering the units and should not have to be changed.

11.1.2 Mounting transform

If the calibrated CubeStar measured vectors does not match with expected values, it could be because of incorrect mounting transform. See the CubeADCS Reference Manual [R01] for an example on how to configure/determine the mounting angles for the *Set Star Tracker Configuration* telecommand (TC ID 37).

11.2 Capture, save and download a CubeStar image

The *Save Image Command* (TC ID 80) can be used to capture and save a CubeSenses camera image in the SD card file system. The *Camera Select* parameter specifies which camera to use, CubeStar = 2. The *Image Size* parameter specifies the resolution of the camera image:

5. 1024 x 1024 pixels (100% resolution)
6. 512 x 512 pixels (50% resolution)
7. 256 x 256 pixels (25% resolution)
8. 128 x 128 pixels (12.5% resolution)
9. 64 x 64 pixels (6.25% resolution)

The image file on the SD card can then be downloaded by the file transfer process described in the CubeADCS Reference Manual [R01]. These images can then be inspected on the ground to ensure that the sun or earth has been correctly captured.

12 Zero bias 3-Axis reaction wheel commissioning

To begin, the satellite must be in a stable Y-momentum control mode (Mode 4) with Full state or MEMS Gyro EKF estimation (Mode 5 or 6). All the reaction wheels (CubeWheel-1, -2 or -3) should be enabled using the *ADCS Power* Control (TC ID 11). Initially the X- and Z-axis reaction wheels must be tested to ensure the correct configuration and polarity. These tests can only be done when the satellite is not in an active wheel control mode, i.e. the control mode must first be set to None (Mode 0). The wheels can then be manually commanded to a reference speed by using the *Set Reference Speed* (TC ID 17). The Y-axis wheel should be commanded to its current measured speed to stay in Y-momentum mode and then the X-axis wheel can be commanded to a constant speed of +200 rpm for a period of 1 minute and then commanded back to 0 rpm before re-enabling the Y-momentum wheel controller (Mode 4).

The test is described in Table 15 below. If the X-axis wheel has the correct polarity the influence on the body angular rates will be similar as the simulation result shown in Figures 12 and 13, i.e. the X-axis rate will jump in the opposite direction as the X-axis commanded wheel speed change.

If the satellite is again stabilized in a Y-momentum mode with low body rates the whole process (similar to Table 13) can be repeated for the Z-axis wheel. See Figure 14 for Z-axis rate change.

Table 15: X-wheel polarity test

Prerequisites	Satellite must be in a stable Y-momentum mode with low angular rates in the body axes as estimated and measured by the MEMS rate sensors	
Command sequence	**Command**	**Parameters**
	Power Control (TC 11)	CubeControl Signal, Motor Power and CubeWheel-1,-2,-3 = On (1) All others = Default
	Set Control Mode (TC 13)	Mode = None (0)
	Set Estimation Mode (TC 14)	Mode = Full State or Gyro EKF (5 or 6)
	Wheel speed command (TC 17)	Commanded X Speed = 200 [RPM] Commanded Y Speed = Measured speed Commanded Z Speed = 0 [RPM]
	Delay	1 min
	Wheel speed command (TC 17)	Commanded X Speed = 0 [RPM] Commanded Y Speed = Measured speed Commanded Z Speed = 0 [RPM]
	Set Control Mode (TC 13)	Mode = Y-momentum (4)
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	1s
	Estimated Angular Rates (TLM 147)	1s
	Estimated Attitude Angles (TLM 146)	1s
	Rate Sensor Rates (TLM 155)	1s
	Measured wheel speed (TLM 156)	1s
Duration	1 pass	
Test condition	• Observe measured wheel speed match the commanded speed. • Observe the satellite measured MEMS angular X-rate jumps negative when the X-wheel ramps to 200 rpm, and jumps positive again when the X-wheel is stopped. • The Z-rate change slower in the same direction as the X-rate jumps.	

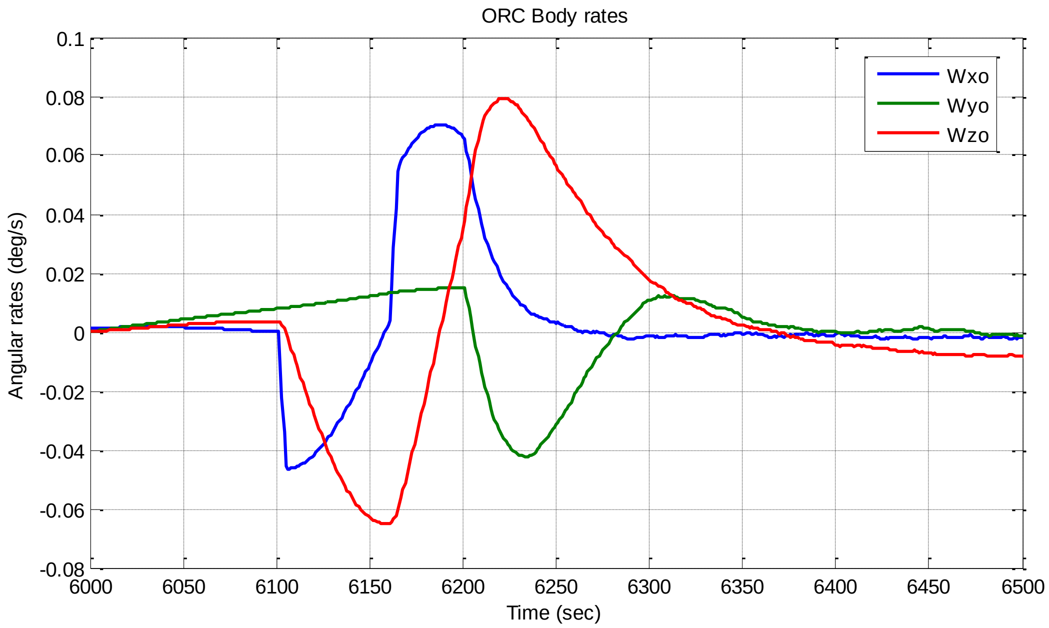


Figure 12: Orbit referenced body angular rate disturbance with X-axis wheel +200 rpm pulse disturbance

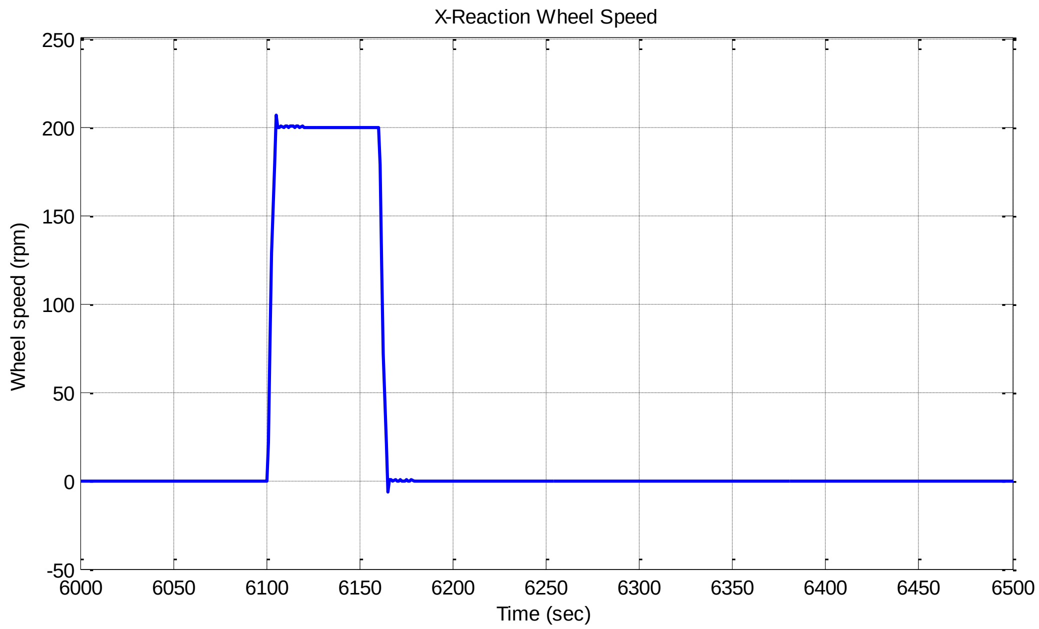


Figure 13: X-axis reaction wheel speed reference pulse

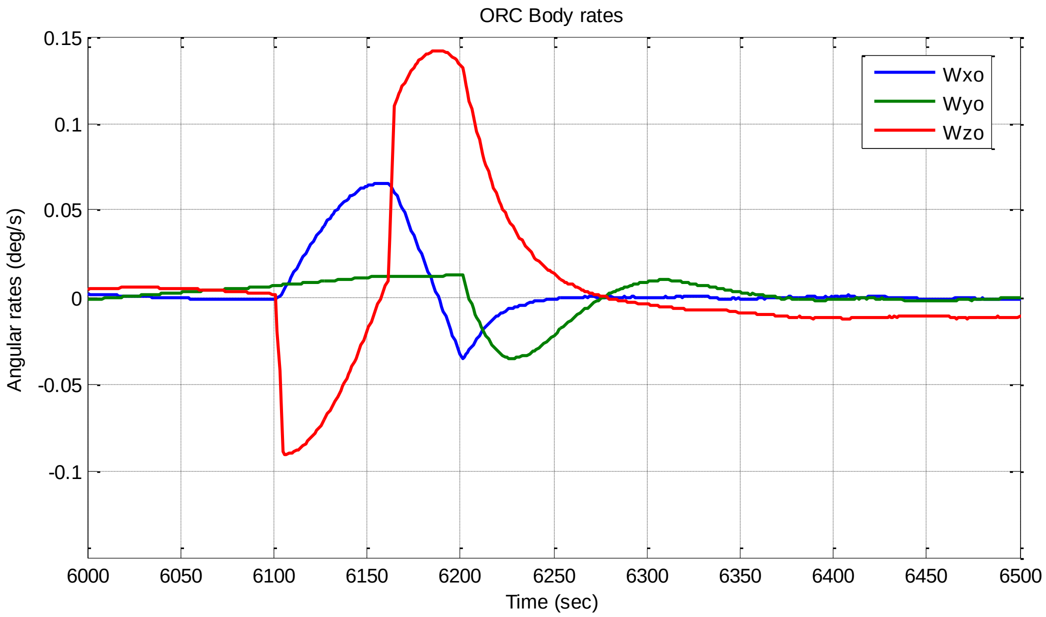


Figure 14: Orbit referenced body angular rate disturbance with Z-axis wheel +200 rpm pulse disturbance

The next step will be to enable the *XYZ-Wheel control mode* (TC ID 13, Mode = 5) when the satellite is in a stable Y-Wheel momentum stabilized steady state mode and a full state EKF estimator with at least the CubeSense Sun and Nadir sensor active. Due to large unmodelled disturbance torques, better results can sometimes be obtained with the MEMS Gyro EKF (Estimation mode = 6). It is always a good idea to ensure small rate sensor (gyro) offsets (bias) before this estimation mode is enabled. The rate sensor offsets can be determined best while in Y-Wheel momentum mode, i.e. when the satellite is in a stable nadir pointing attitude. The average measured output of the X-, Y- and Z-axis rate sensors can then be calculated by sampling these sensors for about 5 minutes. The average rate sensor bias can then be computed as follows:

$$\omega_{X_{bias}} = average[\omega_X(i)]$$

$$\omega_{Y_{bias}} = average[\omega_Y(i)] - \omega_{orbit}$$

$$\omega_{Z_{bias}} = average[\omega_Z(i)]$$

These rate sensor bias values can be corrected using the *Set Rate Sensor Configuration* telecommand (TC ID 36). Then the MEMS Gyro EKF can be selected (TC ID 14, Estim Mode = 6). The gyro EKF will then continuously estimate any bias drift and the satellite's attitude quaternion using the magnetometer and CubeSense Sun and Nadir sensor measurements (in eclipse only the magneto-meter measurements will be available). If CubeStar is also enabled, the star vector measurements can be utilized throughout the orbit for more accurate estimates in both the Full State EKF and the MEMS Gyro EKF. See Table 16 for the typical initial commissioning steps of the zero bias 3-axis reaction wheel controller.

Table 16: XYZ Reaction Wheel Control Commissioning

Prerequisites	Satellite must be in a stable Y-Momentum wheel mode with low angular rates in the body axes as estimated and measured by the MEMS rate sensors. Calculated the MEMS rate sensor bias values as described in this paragraph.	
Command sequence	**Command**	**Parameters**
	Power Control (TC 11)	CubeControl Signal, Motor Power and CubeWheel-1,-2,-3 = On (1) All others = Default
	Set Rate Sensor Configuration (TC 36)	X-, Y-, Z-Rate Sensor Offsets Rate Sensor Multiplier = 1
	Set Estimation Mode (TC 14)	Mode = MEMS Gyro EKF Mode (6)
	Delay	1 orbit (ensure Gyro EKF estimator convergence in Y-Momentum wheel control mode)
	Set Control Mode (TC 13)	Mode = XYZ-Reaction wheel control (5)
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s
	Estimated Attitude Angles (TLM 146)	10s
	Estimated Gyro Bias (TLM 161)	10s
	Estimation Innovation (TLM 162)	10s
	Magnetic Field Vector (TLM 151)	10s
	Fine Sun Vector (TLM 153)	10s
	Nadir vector (TLM 154)	10s
	Rate Sensor Rates (TLM 155)	10s
	Measured Wheel Speeds (TLM 156)	10s
	Magnetorquer Command (TLM 157)	10s
	Wheel Speed Commands (TLM 158)	10s
	IGRF Modelled Vector (TLM 159)	10s
	Quaternion Error Vector (TLM 163)	10s
Duration	1 pass	
Test condition	• Observe measured wheel speed match the commanded speed. • Observe EKF performance (innovation vector magnitude). • Observe XYZ-Reaction wheel control performance (Quaternion error vector).	

The next couple of figures show the simulation result of a 3U CubeSat in a 550 km sun-sync LTDN 10h30 orbit. During the first orbit the satellite started at t = 100 sec in a Y-Momentum wheel control mode from an initial RPY attitude = 0°, 2°, -2°. A MEMS gyro EKF was used to estimate the attitude from magnetometer and CubeSense Sun and Nadir sensor measurements starting at t = 0 sec. During the second orbit at t = 6000 sec the zero bias XYZ-Reaction wheel controller was enabled.

Figure 15 shows the true satellite's attitude and it can be seen that during the eclipse period (approx. 1900-3900 sec and 7500-9500 sec) the attitude estimation error increase due to magnetometer only measurements. In Y-Momentum wheel control mode the attitude errors stay below 2° and in XYZ_Reaction wheel control mode the attitude errors stay below 0.5°. These errors can improve significantly with CubeStar measurements added to the EKF in eclipse. Figure 16 shows the true ORC referenced body rates. Figure 17 shows the XYZ-Wheel speeds; it is clear that the Y-Wheel momentum bias is dumped quickly once the zero bias XYZ-Reaction wheel controller is enabled with magnetic control momentum dumping.

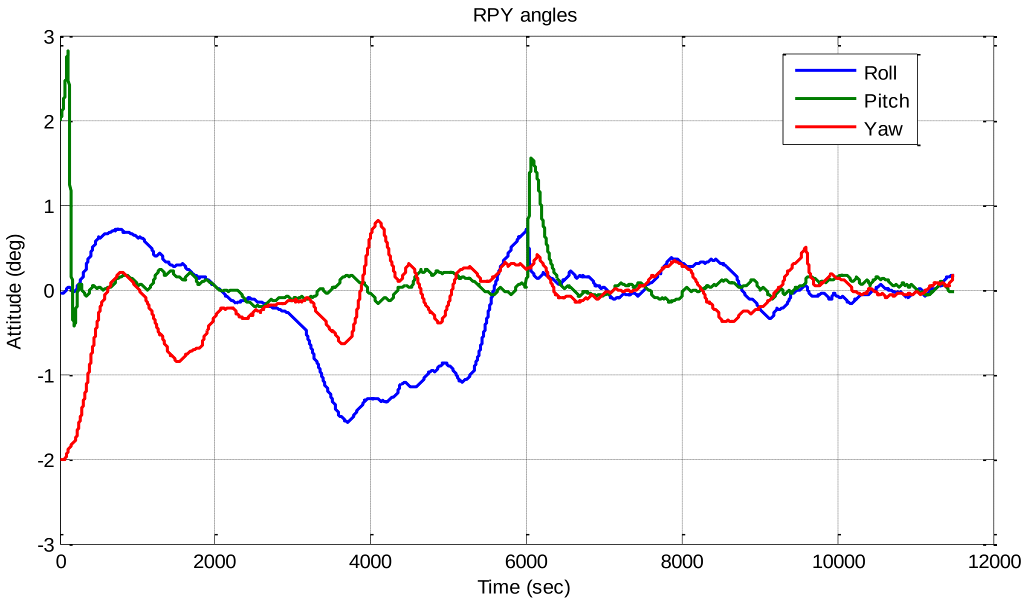


Figure 15: True RPY attitude of the satellite during Y-Momentum wheel and zero bias XYZ-Reaction wheel control

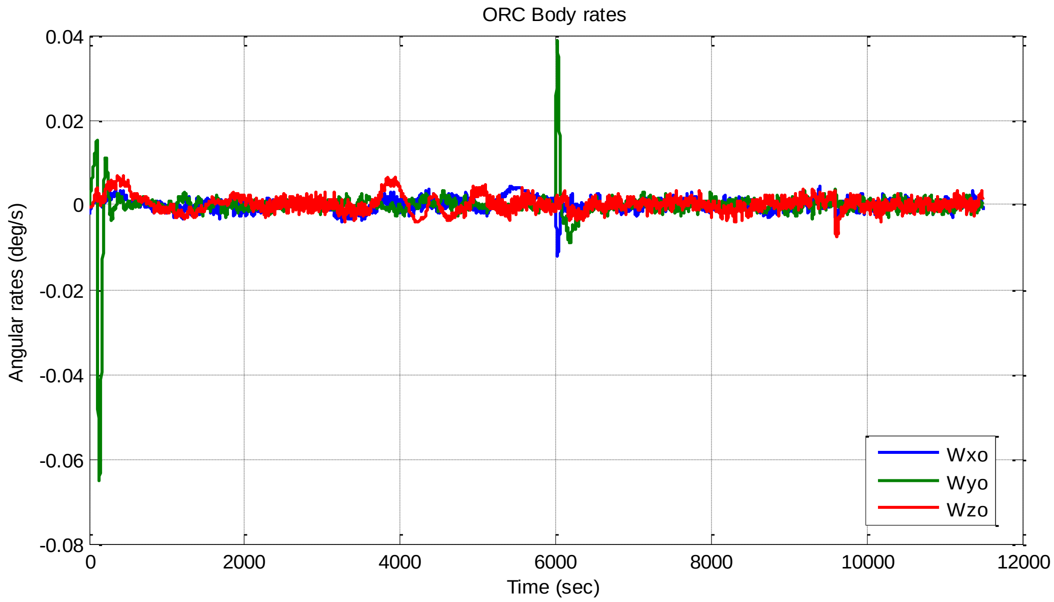


Figure 16: True ORC body rates during Y-Momentum wheel and zero bias XYZ-Reaction wheel control

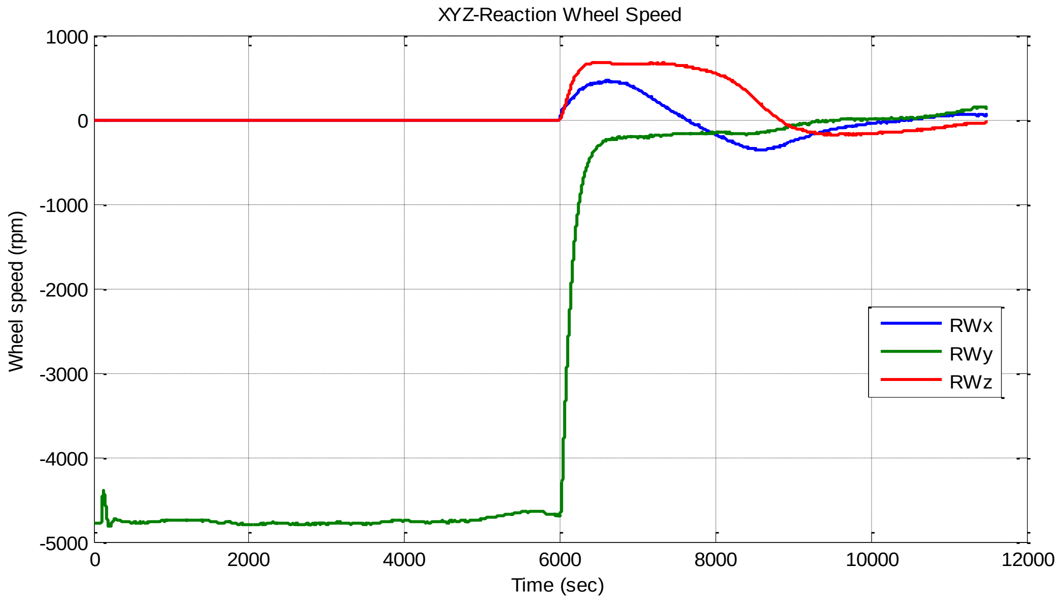


Figure 17: XYZ-Wheel speeds during Y-Momentum wheel and zero bias XYZ-Reaction wheel control

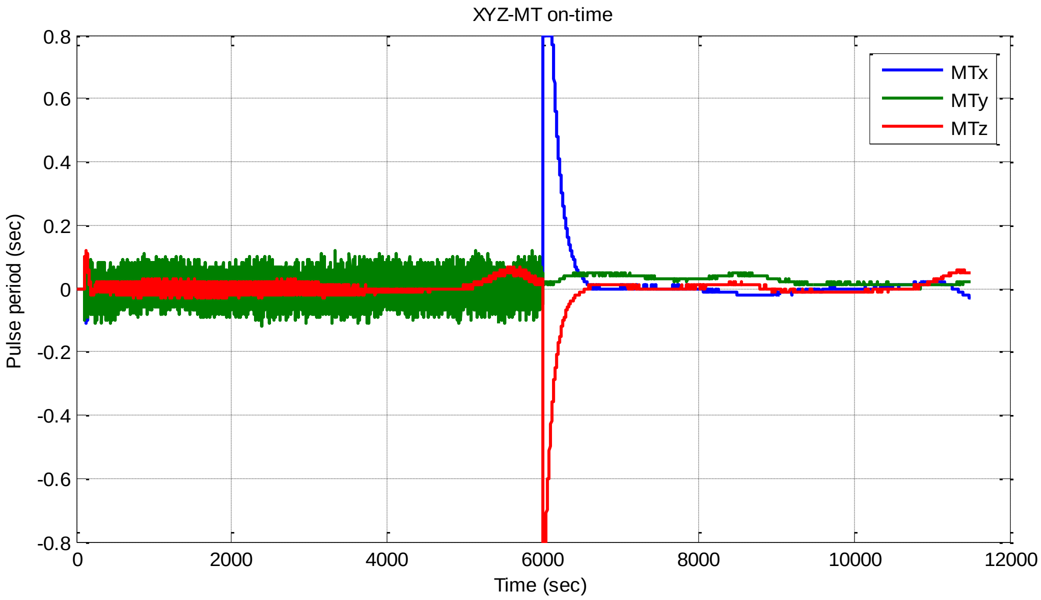


Figure 18: Magnetorquer on-time during Y-Momentum wheel and zero bias XYZ-Reaction wheel control

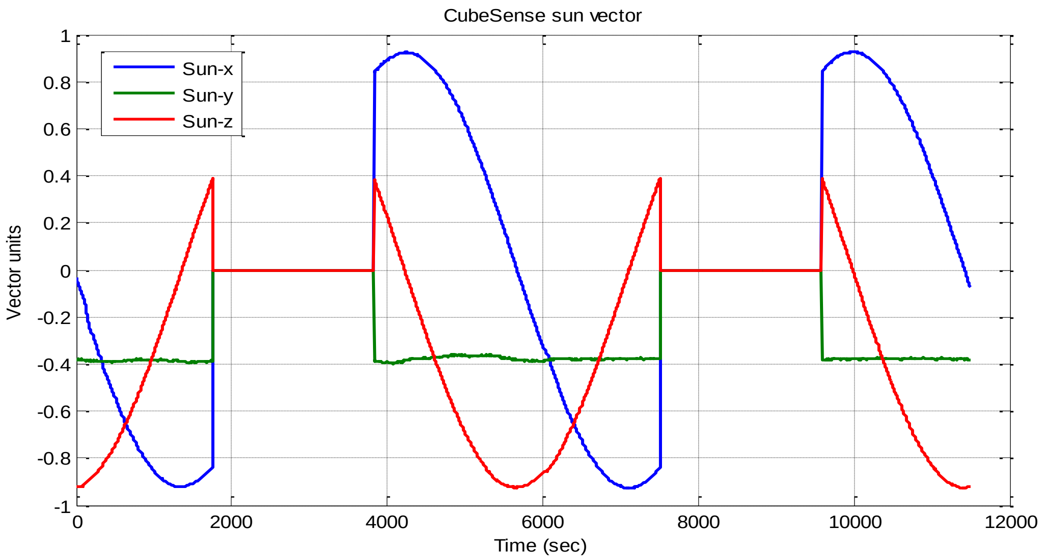


Figure 19: CubeSense sun vector measurement during Y-Momentum wheel and zero bias XYZ-Reaction wheel control

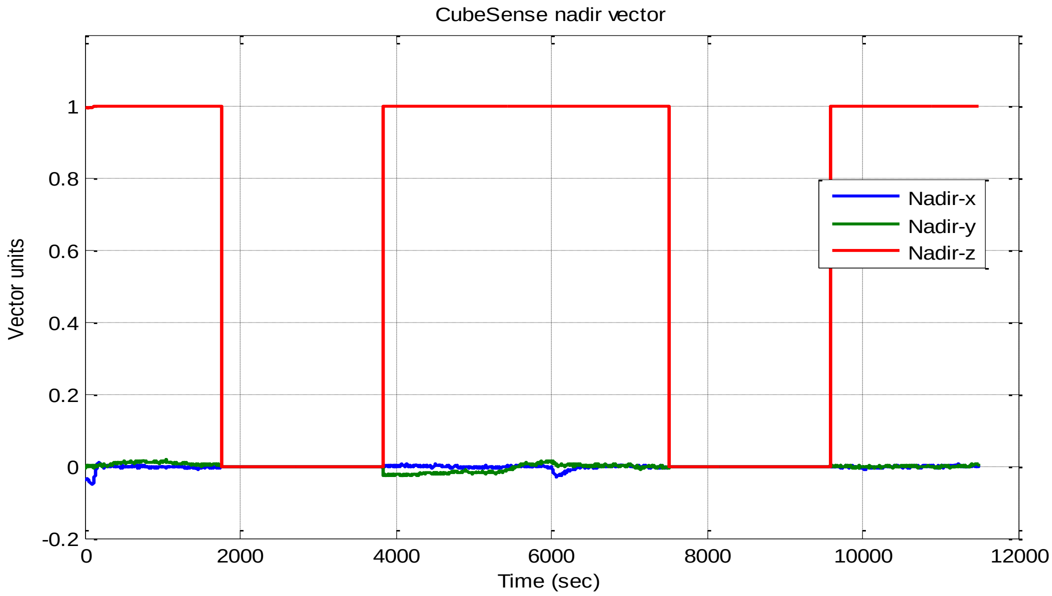


Figure 20: CubeSense nadir vector measurement during Y-Momentum wheel and zero bias XYZ-Reaction wheel control

13 Sun tracking 3-axis control

When the XYZ-reaction wheel 3-axis controller gives satisfactory performance with the MEMS rate EKF, the sun tracking controller can be enabled during the sunlit part of an orbit. In eclipse this control mode will automatically revert back to nadir pointing. See Table 17 for the typical initial commissioning steps of the sun tracking 3-axis reaction wheel controller.

Table 17: Sun Tracking 3-axis Control Commissioning

Prerequisites	Satellite must be in a stable nadir pointing 3-axis reaction wheel mode with angular rates in the body axes as estimated and measured by the MEMS rate sensors and EKF.	
Command sequence	**Command**	**Parameters**
	Power Control (TC 11)	CubeControl Signal, Motor Power and CubeWheel-1,-2,-3 = On (1) All others = Default
	Set Rate Sensor Configuration (TC 36)	X-, Y-, Z-Rate Sensor Offsets Rate Sensor Multiplier = 1
	Set Estimation Mode (TC 14)	Mode = MEMS Gyro EKF Mode (6)
	Delay	1 orbit (ensure Gyro EKF estimator convergence in XYZ-reaction wheel 3-axis control mode)
	Set Control Mode (TC 13)	Mode = Sun Tracking control (6)
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s

	Estimated Attitude Angles (TLM 146)	10s
	Estimated Gyro Bias (TLM 161)	10s
	Estimation Innovation (TLM 162)	10s
	Magnetic Field Vector (TLM 151)	10s
	Fine Sun Vector (TLM 153)	10s
	Nadir vector (TLM 154)	10s
	Rate Sensor Rates (TLM 155)	10s
	Measured Wheel Speeds (TLM 156)	10s
	Magnetorquer Command (TLM 157)	10s
	Wheel Speed Commands (TLM 158)	10s
	IGRF Modelled Vector (TLM 159)	10s
	Quaternion Error Vector (TLM 163)	10s
Duration	1 pass	
Test condition	• Observe measured wheel speed match the commanded speed. • Observe EKF performance (innovation vector magnitude). • Observe the RPY attitude changes for sun tracking (see Fig.21). • Observe XYZ-Reaction wheel control performance (Quaternion error vector).	

Figure 21 shows the RPY attitude angles during sun tracking in the sunlit part of an orbit, in eclipse the RPY attitude will be zero (nadir pointing). Figure 22 shows the CubeSense sun sensor measurement with boresight and solar panel normal vector pointing to the sun during sun tracking. Figure 23 shows the XYZ-Reaction wheel angular momentum during sun tracking, the large excursions at the start and end of the sunlit period of the orbit are the result of manoeuvres from nadir to sun pointing and back.

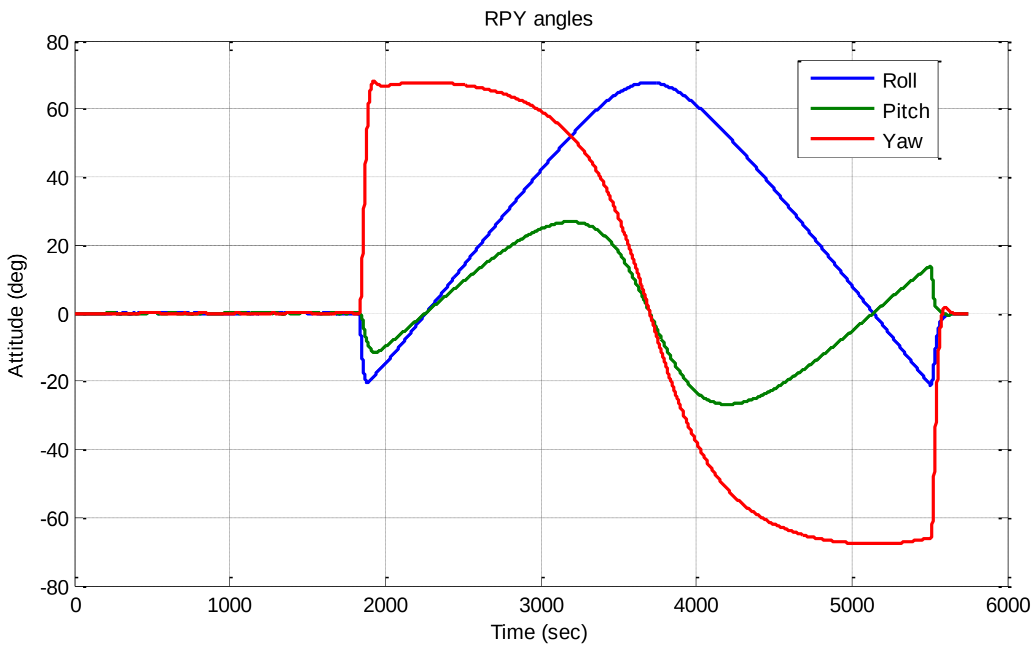


Figure 21: True RPY attitude during Sun tracking reaction wheel control

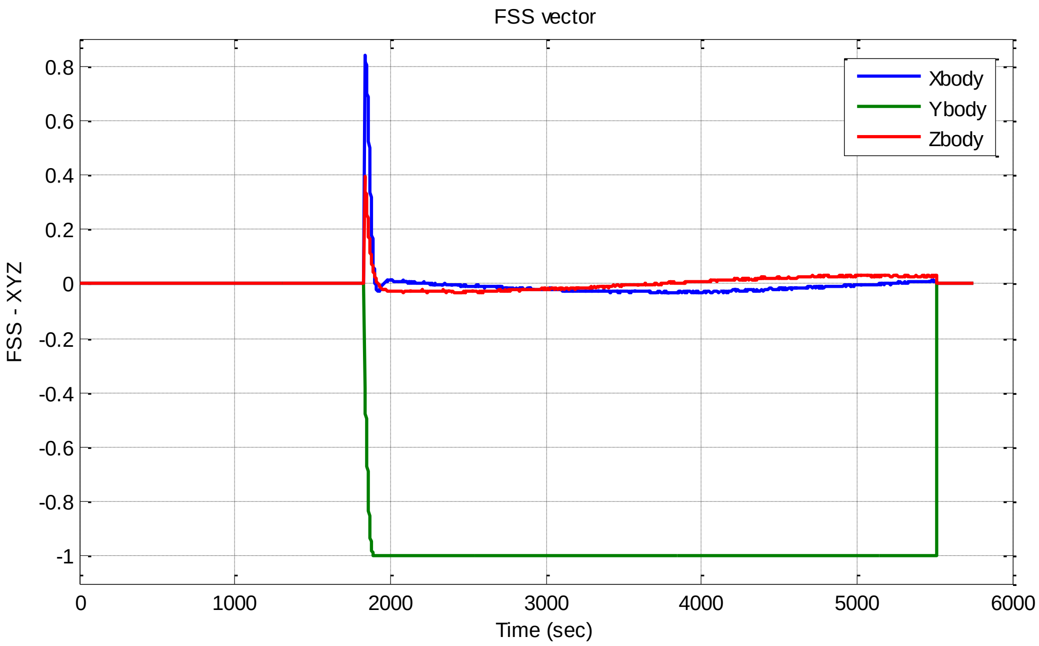


Figure 22: CubeSense sun vector measurement during Sun tracking reaction wheel control during the sunlit part of an orbit

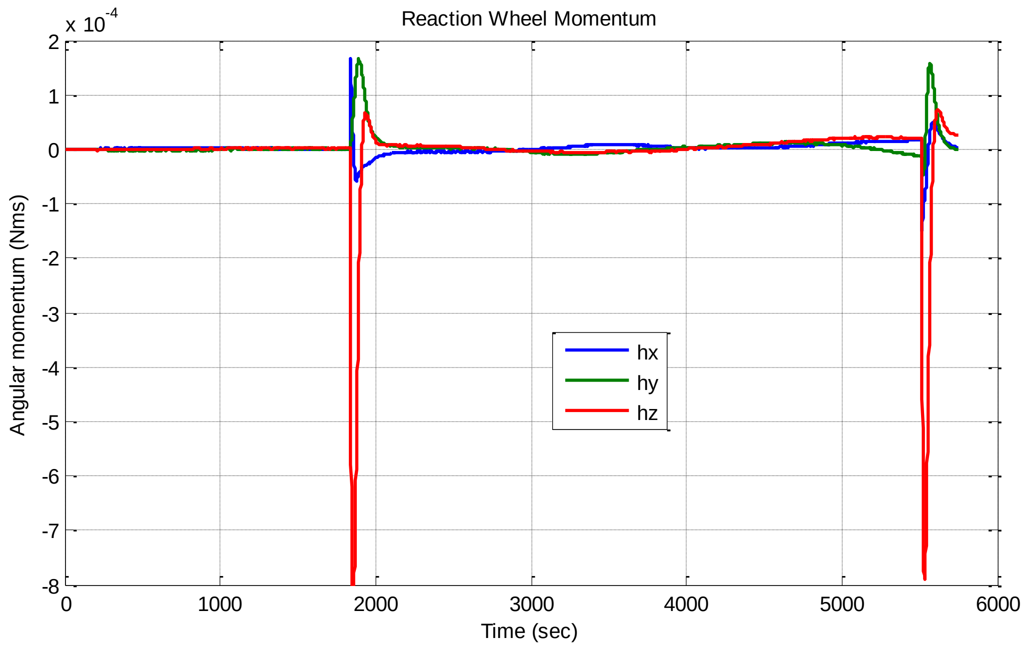


Figure 23: XYZ-Reaction wheel angular momentum during Sun tracking reaction wheel control during the sunlit part of an orbit

14 Ground target tracking controller

When the XYZ-reaction wheel 3-axis controller gives satisfactory performance with the MEMS rate EKF, the sun tracking controller can be enabled close to a target area on the ground. Figure 24 shows tracking control of a ground target during an overhead pass (at max 90° elevation). Figure 25 shows the RPY attitude errors and Fig 26 the XYZ reaction wheel angular momentum during the manoeuvres towards, during and back from the target tracking control mode to nadir pointing control mode.

Table 18: Target Tracking 3-axis Control Commissioning

Prerequisites	Satellite must be in a stable nadir pointing 3-axis reaction wheel mode with angular rates in the body axes as estimated and measured by the MEMS rate sensors and EKF.	
Command sequence	**Command**	**Parameters**
	Power Control (TC 11)	CubeControl Signal, Motor Power and CubeWheel-1,-2,-3 = On (1) All others = Default
	Set Rate Sensor Configuration (TC 36)	X-, Y-, Z-Rate Sensor Offsets Rate Sensor Multiplier = 1
	Set Estimation Mode (TC 14)	Mode = MEMS Gyro EKF Mode (6)
	Delay	1 orbit (ensure Gyro EKF estimator convergence in XYZ-reaction wheel 3-axis control mode)
	Set Ground Target Reference (TC 55)	Geocentric longitude, latitude and altitude of an approaching ground target close to the ground track of the satellite (See Section 14.1)
	Minimum 300 seconds before closest range to target: Set Control Mode (TC 13)	Mode = Target Tracking control (7)
	Minimum 300 seconds after closest range to target: Set Control Mode (TC 13)	Mode = Nadir pointing control (5)
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Estimated Angular Rates (TLM 147)	10s
	Estimated Attitude Angles (TLM 146)	10s
	Estimated Gyro Bias (TLM 161)	10s
	Estimation Innovation (TLM 162)	10s
	Magnetic Field Vector (TLM 151)	10s
	Fine Sun Vector (TLM 153)	10s
	Nadir vector (TLM 154)	10s
	Rate Sensor Rates (TLM 155)	10s
	Measured Wheel Speeds (TLM 156)	10s
	Magnetorquer Command (TLM 157)	10s
	Wheel Speed Commands (TLM 158)	10s

	IGRF Modelled Vector (TLM 159)	10s
	Quaternion Error Vector (TLM 163)	10s
	Satellite LLH position (TLM 150)	10s
	Commanded attitude angles (TLM 199)	10s
Duration	1 pass	
Test condition	• Observe measured wheel speed match the commanded speed. • Observe EKF performance (innovation vector magnitude). • Observe the RPY attitude changes during target tracking (see Fig.24). • Observe XYZ-Reaction wheel control performance (Quaternion error vector). • Observe the satellite Lat/Lon/Alt position near the target area.	

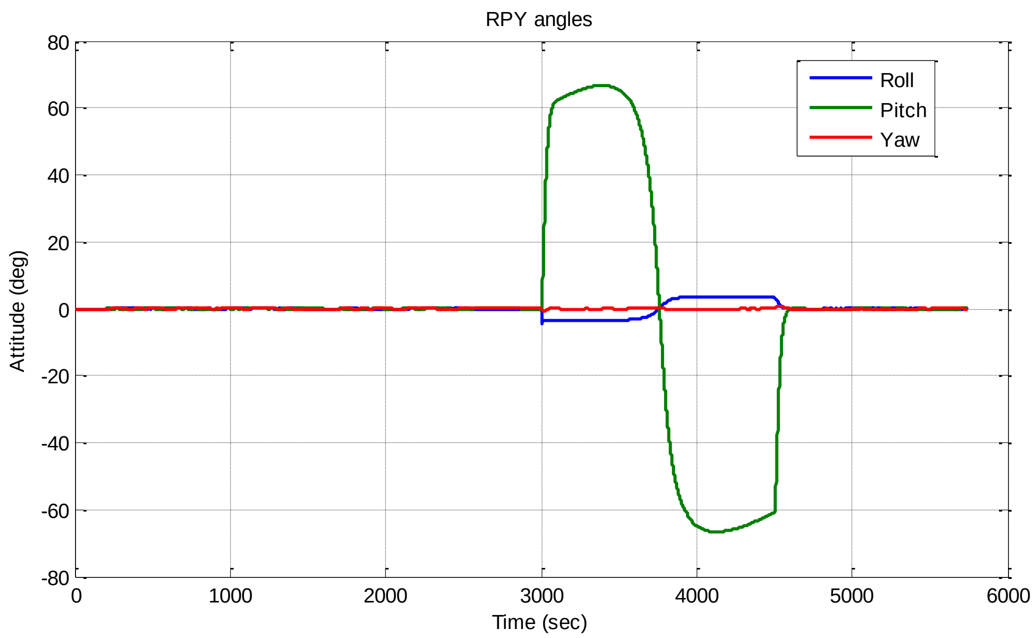


Figure 24: True RPY attitude during ground target tracking reaction wheel control

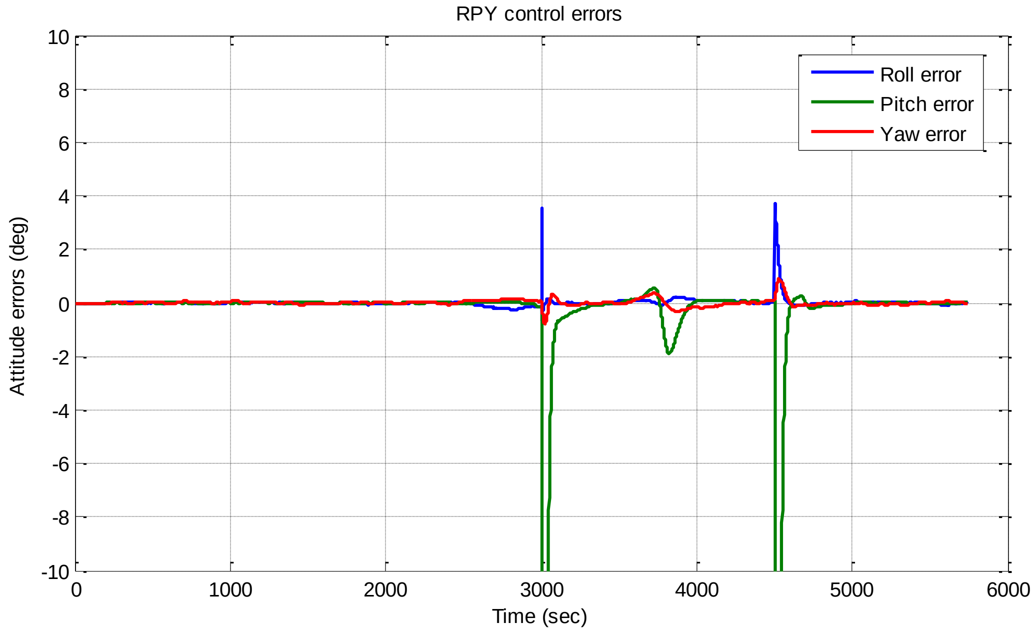


Figure 25: RPY tracking errrors during ground target tracking reaction wheel control

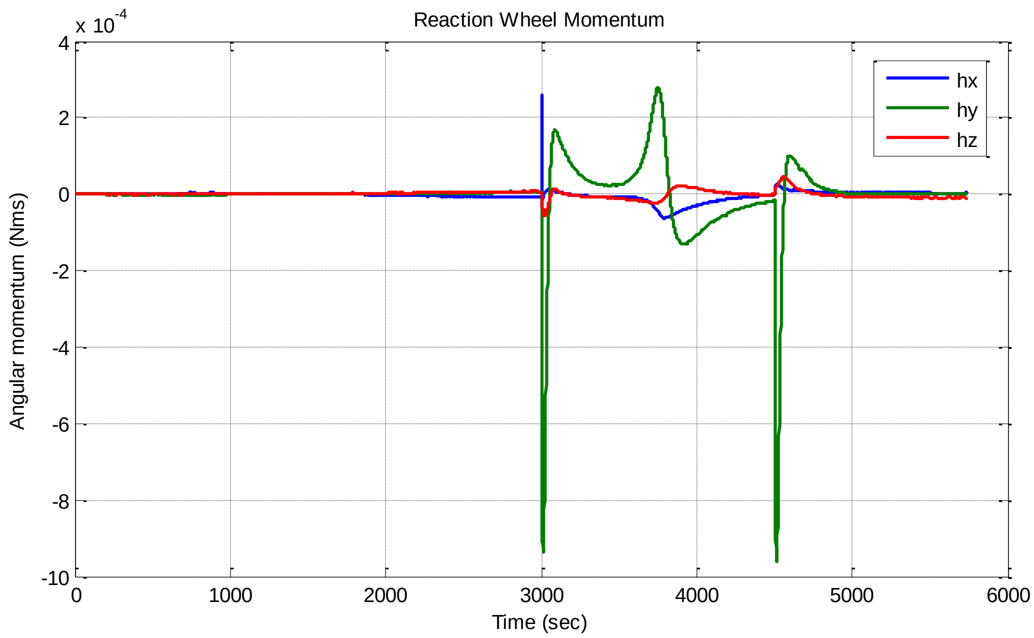


Figure 26: XYZ-Reaction wheel angular momentum during ground target tracking reaction wheel control

14.1 Calculation steps of Ground Target Reference (TC ID 55 parameters)

1. Use *Google Earth* and orbit propagator software (e.g. *Nova, Orbitron*) to obtain the ground target coordinates and future Unix time at closest range (i.e. when the target is

closest to the sub-satellite track)

E.g. For *TARGET* at SSP:
φ_{gd} = 34° 05′ 31″ S = -34.0919°, θ_{gc} = 21° 16′ 27″ E = +21.2742°, *Alt* = 100 meter.

2. Calculate geocentric latitude: $\varphi_{gc} = \arctan\left(\left(1-e_\theta^2\right)\tan\left(\varphi_{gd}\right)\right) \quad with \quad e_\theta = 0.081819$
   e.g. for *TARGET*: φ_{gd} = -34.0919°, therefore φ_{gc} = -33.9135°.

3. Calculate target (site) radius:

$$r_{site} = R_\theta \sqrt{1-e_\theta^2 \sin^2\left(\varphi_{rd}\right)} \quad with \quad R_\theta = 6378.14\,km \quad and \quad \varphi_{rd} = \arcsin\left(\frac{\sin\left(\varphi_{gc}\right)}{\sqrt{1-e_\theta^2 \cos^2\left(\varphi_{gc}\right)}}\right)$$

   e.g. for *TARGET*: φ_{rd} = -34.0026°, therefore r_{site} = 6371.46 *km*.

4. Calculate target altitude relative to equatorial radius R_θ: $\Delta r = r_{site} + Alt - R_\theta$
   e.g. for *TARGET*: Δ*r* = -6.58 *km*

5. Parameters for TC ID 55:
   (i) Geocentric latitude φ_{gc} = -33.91 *deg*
   (ii) Geocentric longitude θ_{gc} = 21.27 *deg*
   (iii) Relative altitude Δ*r* = -6580 *meter*

15 GPS receiver commissioning

As the GPS receiver is not required by the ADCS software to function, the GPS can be enabled at any time without affecting the ADCS performance. The GPS receiver must first be powered by a direct command to the EPS of the satellite (a switched 3.3V power line). Thereafter the steps in Table 19 below can be followed by first enabling the GPS LNA, using an ADCS power command.

Table 19: GPS receiver Commissioning

Prerequisites	Satellite must be in a stable nadir pointing 3-axis reaction wheel mode with angular rates in the body axes as estimated and measured by the MEMS rate sensors or Full State EKF	
Command sequence	**Command**	**Parameters**
	Power Control (TC 11)	GPS LNA = On (1) All others = Default
Telemetry logging	**Telemetry frame**	**Period**
	Current Unix time (TLM 140)	10s
	Satellite LLH position (TLM 150)	10s
	Raw GPS Status (TLM 176)	10s
	Raw GPS Time (TLM 177)	10s

	Raw GPS X (TLM 178)	10s
	Raw GPS Y (TLM 179)	10s
	Raw GPS Z (TLM 180)	10s
Duration	1 orbit	
Test condition	• Observe the GPS status parameters if enough satellites were tracked and the GPS solution status is successful. • Observe the GPS time solutions and compare to Unix time. • Observe the ECEF XYZ position and velocity solutions, compare position to satellite WGS-84 latitude, longitude, altitude SGP4 values.	

16 Suggested default overpass actions

The following actions should be performed at every overpass:

16.1 Synchronize time

Time is synchronized by sending a single *Set Unix Time* command to the ADCS (TC ID 2).

16.2 ADCS Health

The health of the ADCS is assessed by monitoring the error flags in the ADCS State telemetry, and also the current and temperature telemetry frames. Persistent error flags should be addressed, and caution should be taken when current telemetry values deviate too far from the nominal or default values.

16.3 Check for updates and Upload TLEs

It is important to use up-to-date two-line elements. TLEs are published at regular intervals, and it is recommended that TLEs are updated on the ADCS whenever new ones are available (this does not have to happen on every pass, but typically once daily).