TT&C Design Definition & Justification File [DDJF_TTC]

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Changelog

Date	Version	Author	Details
2020-11-11	1.1 PUBLISHED	AcubeSAT Team	• Added GS-FUN-030 Analysis Requirement close-out • Added additional information on sequence number checks • Elaborated on the recovery countdown timer (Section 3.8) • Revised beacons (Section 3.6.7) • Updated link budget conclusion (Section 4) • Updated beacon intervals and information about the rationale behind the existence of two beacons in (Section 3.6.7)
2020-10-04	1.0 RELEASED	AcubeSAT Team	• Updated dipole antenna information (Section 2.2.2) • Added patch antenna report • Formatting fixes throughout the document • Added Link Margin in Quick Facts table (Section 1)
2020-09-27	0.1 RELEASED	AcubeSAT Team	Initial release

Table Of Contents

List of abbreviations

ACK	Acknowledgment
ADC	Analog-to-Digital Converter
ADCS	Altitude Determination and Control Subsystem
AGC	Automatic Gain Control
ASM	Attached Sync Marker
AUTH	Aristotle University of Thessaloniki
BCH	Bose–Chaudhuri–Hocquenghem Code
BER	Bit Error Rate
BPSK	Binary Phase Shift-Keying
CAN	Controller Area Network
CANFD	Controller Area Network Flexible Data-Rate
CCSDS	Consultative Committee for Space Data Systems
COMMS	Communications
COTS	Commercial off-the-Shelf
CUC	CCSDS Unsegmented Time Code
CW	Continuous Wave
DAC	Digital-to-Analog Converter
DSP	Digital Signal Processing
ECSS	European Cooperation for Space Standardization
FARM	Frame Acceptance and Reporting Mechanism
FDU	Frame Data Unit
FECF	Frame Error Control Field
FPGA	Field-Programmable Gate Array
FSK	Frequency Shift-Keying
FSPL	Free Space Path Losses
GMSK	Gaussian Minimum-Shift Keying
GS	Ground Station
HMAC	Hash-based Message Authentication Code
HPBW	Half Power Beamwidth
HPT	High Priority Telecommands
LEOP	Launch and Early Operations Phase
LSF	Libre Space Foundation
MAC	Message Authentication Code
MSK	Minimum Shift-Keying
OBC	On-Board Computer
OOK	On-Off Keying
OQPSK	Offset Quadrature Phase-Shift Keying
PCB	Printed Circuit Board
PUS	Packet Utilization Standard
QPSK	Quadrature Phase-Shift Keying
RF	Radio frequency
RX	Receiver
Rx	Receive
SC	Spacecraft
SDR	Software Defined Radio
SPP	Space Packet Protocol
SU	Science Unit
TC	Telecommand
TM	Telemetry
TT&C	Telemetry, Tracking & Command
TX	Transmit
Tx	Transmit
UHF	Ultra High Frequency
WPM	Words Per Minute

Introduction

The TT&C subsystem is responsible for ensuring the reliability of the communication between the spacecraft and the Ground Station by utilizing the *SatNOGS COMMS* board and two antennas, one for the UHF band and one for the S-band. This document describes the communication protocols used by the TT&C subsystem as well as the modulation and error correction codes applied to the transmitted and received streams of data. It also introduces the antennas employed by the AcubeSAT mission, located on the spacecraft. It provides insight about the operability of the TT&C subsystem during the different modes.

The COMMS board is responsible for the signal processing and more specifically for the modulation, error correction, as well as the filtering and power amplification of the TX and RX emissions of each link. Additionally, the communication protocols that are mentioned below are also handled by this board. The latter meets the mission's needs of operating in the radioamateur spectrum (UHF and S-band) and the coding schemes along with the RF capabilities provided, fulfill the requirements of low BER for all links and high data rate for the payload data.

The widely used UHF band is utilized for receiving TCs and transmitting TM. Because of bandwidth limitations, S-band data was chosen for downlinking payload data since a particularly high data rate is required to downlink all the images in time. We operate on the radioamateur bands because of our general philosophy of giving back to the community. Additionally, the radioamateur community is able to receive and decode our beacons.

Analyses for both the dipole and the directional patch antenna are also included in this document and serve as a justification for their utilization. The dipole antenna is used for both the transmission of TM and reception of TC, while the patch one is used for the transmission of payload data.

For more information on the link and data budgets it's recommended to read the full analysis report *ASAT_DDJF_LINK_ARPT*. It's also suggested to look further into *ASAT_DDJF_GS* which explains the design and functionality of the Ground Station entity.

Applicable Documents

#	Document Number	Document Title	Version	Date
AD1	ASAT_DDJF_LINK_ARPT	Link and Data Budget Analysis Report Design Definition & Justification File	1.1	2020-11-11
AD2	ASAT_DDJF_GS	GS Design Definition & Justification File	1.1	2020-11-11
AD3	AcubeSAT-COM-G-011	2.4 GHz circularly-polarized patch antenna for the AcubeSAT mission	2.0	2020-10
AD4	AcubeSAT-COM-G-025	A UHF half-wave dipole antenna for the AcubeSAT mission	1.0	2020-10
AD5	ASAT_MDO	Mission Description & Operations Plan	1.1	2020-11-12

Reference Documents

[1] Libre Space Foundation. *System Design Document. SatNOGS COMMS*. Version 0.5. July 23, 2020.

[2] AcubeSAT Team. *MCH Design Definition & Justification File*. ASAT_DDJF_MCH. Version 1.1. Nov. 12, 2020.

[3] The Consultative Committee for Space Data Systems. *TM Space Data Link Protocol*. CCSDS-132.0-B-2. Version 2.0. Sept. 2015.

[4] The Consultative Committee for Space Data Systems. *TC Space Data Link Protocol*. CCSDS-232.0-B-3. Version 3.0. Sept. 2015.

[5] European Cooperation for Space Standardization. *Telemetry and telecommand packet utilization*. ECSS-E-ST-70-41C. Apr. 15, 2016.

[6] The Consultative Committee for Space Data Systems. *Space Packet Protocol*. CCSDS-133.0-B-2. Version 2.0. June 2020.

[7] The Consultative Committee for Space Data Systems. *Radio Frequency and Modulation Systems–Part 1: Earth Stations and Spacecraft*. CCSDS-401.0-B-29-S. Version 29.0. Mar. 2019.

[8] The Consultative Committee for Space Data Systems. *Bandwidth-Efficient Modulations–Summary of Definition, Implementation, and Performance*. CCSDS-413.0-G-3. Version 3.0. Feb. 2018.

[9] The Consultative Committee for Space Data Systems. *TM Synchronization and Channel Coding*. CCSDS-131.0-B-3. Version 3.0. Sept. 2017.

[10] European Cooperation for Space Standardization. *SpaceWire – CCSDS packet transfer protocol*. ECSS-E-ST-50-53C. Feb. 5, 2010.

[11] The Consultative Committee for Space Data Systems. *Technical Corrigendum 1 to CCSDS 232.1-B-2, Issued September 2010*. CCSDS-232.1-B-2. Version 2.1. Apr. 2019.

[12] The Consultative Committee for Space Data Systems. *Technical Corrigendum 1 to CCSDS 231.0-B-2-S, Issued September 2010*. CCSDS-231.0-B-2-S. Version 2.1. Apr. 2013.

[13] The Consultative Committee for Space Data Systems. *Communications Operation Procedure-1*. CCSDS-232.1-B-2. Version 2.0. Sept. 2010.

[14] AcubeSAT Team. *EPS Design Definition & Justification File*. ASAT_DDJF_EPS. Version 1.1. Nov. 9, 2020.

[15] AcubeSAT Team. *OBDH Design Definition & Justification File*. ASAT_DDJF_OBDH. Version 1.1. Nov. 11, 2020.

[16] AcubeSAT Team. *Failure Modes Effect Analysis Report*. ASAT_FMEA. Version 1.1. Nov. 12, 2020.

1 TT&C Quick Facts Table

Parameter	Unit	UHF Uplink	UHF Downlink	S-band Downlink
Frequency	MHz	436.5	436.5	2425
Modulation	-	GMSK	GMSK	OQPSK
Coding	-	Convolutional (R=1/2)	Convolutional (R=1/2)	LDPC (R=4/5)
RF Bandwidth	kHz	20	20	1000
BER	-	10^{-6}	10^{-6}	10^{-6}
Signal power	dBm	-97.3	-106.9	-107.5
Link Margin (Nominal Mode)	dB	18.3	8.7	10.2
Link Margin (Science Mode)	dB	15.3	5.7	-
Link Margin (Safe Mode)	dB	15.3	5.7	-

2 Physical Architecture

The TT&C subsystem requires a robust physical design that permits the operations on both the UHF and S-band. Thus, a COMMS board such as the *SatNOGS COMMS board* fulfils these requirements as it enables the reception and transmission of signals in both bands. The physical design integrates the dipole antenna for the communication in UHF band and the patch antenna for the S-band.

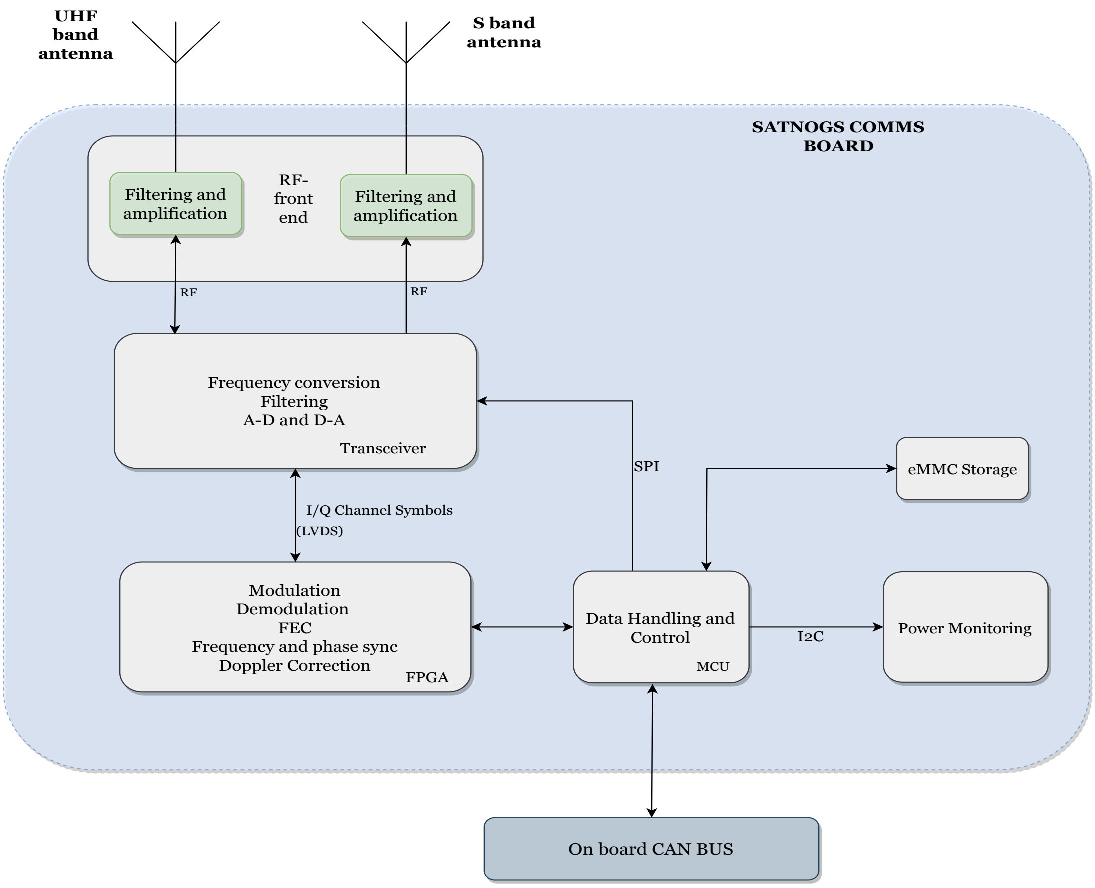

Figure 1: *Data Paths in COMMS subsystem*

The COMMS board provides the capability of processing I/Q samples in both bands of interest and is responsible for the signal processing, the signal filtering and amplification, as well as the communication with the other subsystems through connections with the CAN BUS. It also allows for the implementation of the communication protocols and the encoding schemes that are utilized in our mission.

Additionally, the communication needs to be as independent as possible of the orientation of the satellite in the UHF band. This is made possible by utilizing a non directional dipole antenna. In contrast, the S-band patch antenna is more directional and is employed for higher data rates.

2.1 COMMS Board

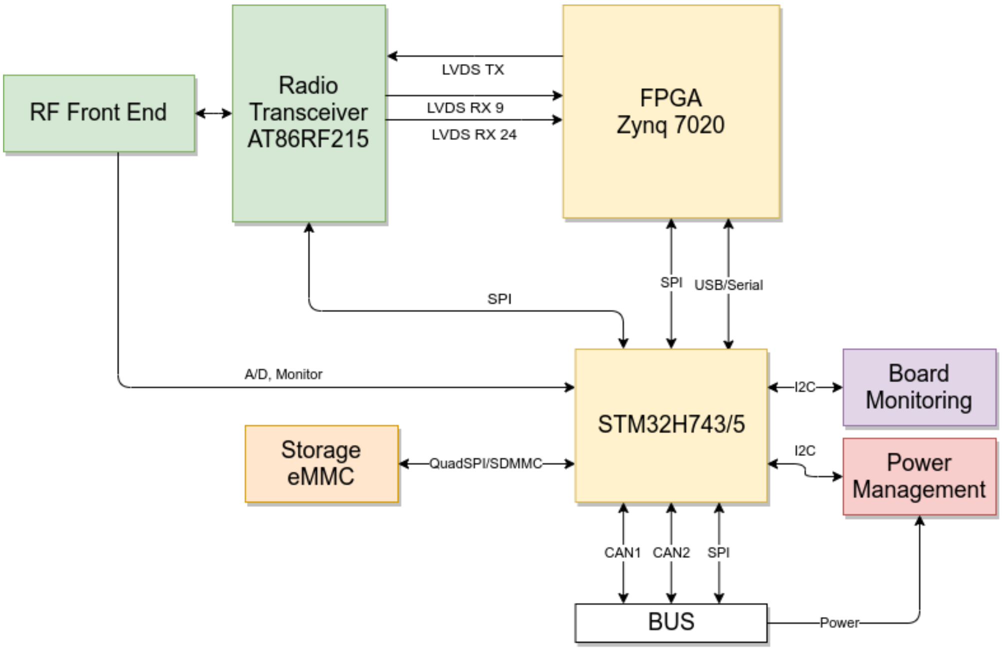

***Figure 2**: SatNOGS COMMS Board System Block Diagram [1]*

The TT&C subsystem will be using the *SatNOGS COMMS* board currently in development by LSF [1] which meets the CubeSat's requirements. The board is based on the AT86RF215 transceiver chip by Atmel which offers a 13-bit I/Q interface with a maximum sampling frequency of 4 MHz.

In the RX chain an AGC algorithm is embedded in the transceiver to take a full advantage of the ADC resolution, with a gain that varies from 0 to 23 dB. The transceiver has a maximum bandwidth of 2 MHz. The DAC follows the same specifications as the ADC and the maximum output bandwidth is 1 MHz The maximum input signal level is -10 dBm while the maximum output is $+14$ dBm.

The *SatNOGS* board uses the RFFC2071 mixer to convert frequencies not covered by the transceiver. Since we expect the CubeSat to operate within the transceiver's supported frequency bands, we don't really need the mixer. However, the final design is pending as of September 2020.

As the AT86RF215 transceiver does not support the CCSDS modulation and coding schemes, its separate I/Q interface is utilized for this purpose. Most of these time-critical DSP tasks required to generate the CCSDS packets are implemented on the *ZYNQ-7020* FPGA. Thus, the COMMS board also supports several CCSDS-compliant modulation schemes, namely BPSK, FSK and MSK on the UHF and MSK, BPSK and QPSK. For error correction, both LDPC and convolutional encoding will be supported, however there are no plans for BCH which will be used for the error correction of TC packets. For this purpose we utilize our own implementation of BCH decoders.

Regarding subsystem communication, the board supports the CANFD data-communication protocol which is also backwards-compatible with classic CAN.

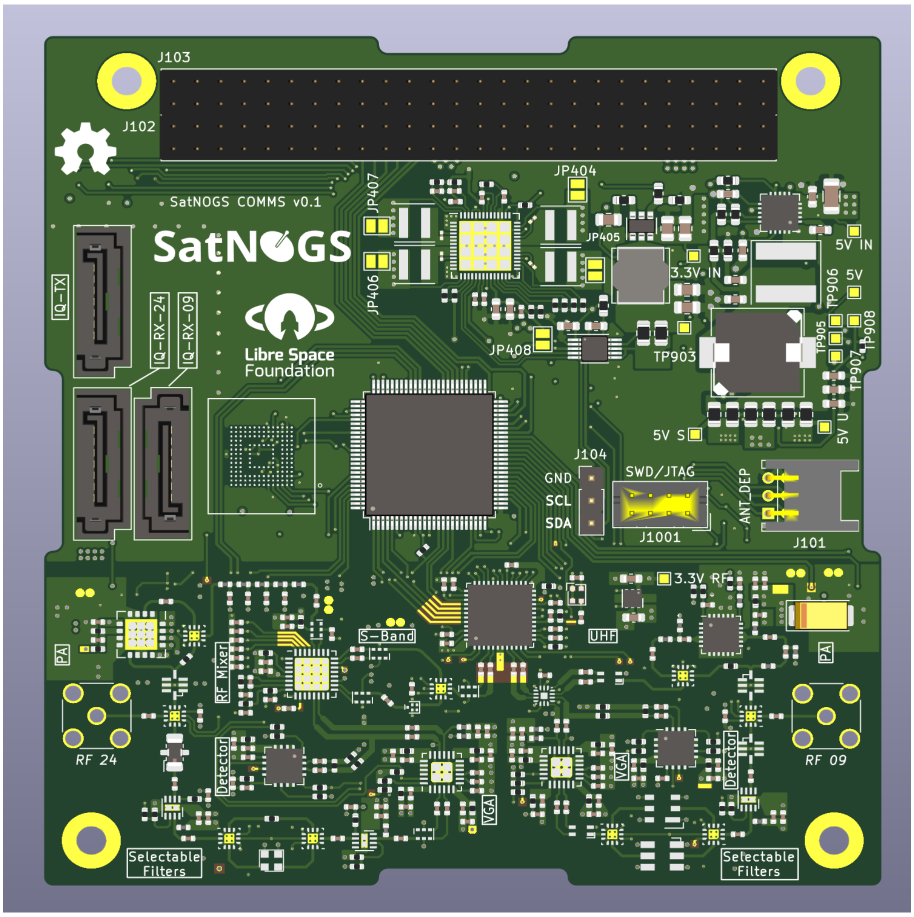

***Figure 3**: Engineering Model of the LSF SatNOGS COMMS board*

2.1.1 Alternative COMMS Board

As the current COMMS Board is still under development, there is an inherent risk in relying on the development team to successfully deliver the final product on time. For this reason, a market search was conducted to identify potential COTS alternatives.

The requirement on transmitting both on UHF and S band greatly restricts our available choices. After extensive search, three alternatives were identified that seemed to - at least partly - satisfy our mission's requirements: an SDR platform by *GOMSPACE*, one by *TOTEM* and *Spacemanic*.

After a careful risk assessment, we decided to proceed with our original choice of the *SatNOGS COMMS* board. The fact that it is open-source and we have access to the latest changes through its GitLab repository allows us to both keep up-to-date with recent developments and potentially jump in to finish the problem if the project fails to meet its expected delivery date. As of September 2020, the PCB schematics and RF front-end is nearly finished, so we only expect to do some work on the currently under-developed software of the board if the need arises.

2.2 Antennas

2.2.1 S-band Patch antenna

An in-house, multilayered, U-Slot, circularly polarized patch antenna is used for the S-band transmission. A prototype of the antenna was constructed using photo-resistive copper-coated FR-4 and epoxy glue. Testing of the model was performed in the anechoic chamber of AUTH. A maximum gain of approximately 4.13 dBi and a minimum HPBW of 98° were measured.

In [AD3] the reader may find a **comprehensive report concerning the development of the patch antenna, as well as the testing procedures and extracted results.**

Requirements close-out — Analysis			
The above document is the close out reference for requirements:			
GS-FUN-130	The S-band ground station antenna shall provide circular polarization with an axial ratio of less than 3 dB.	Compliant at Phase C. Simulation and prototype test results confirm that the axial ratio is less than 3 dB in the whole 2.4-2.45 GHz range.	Sections 5.5, 5.6, & 8.5.3

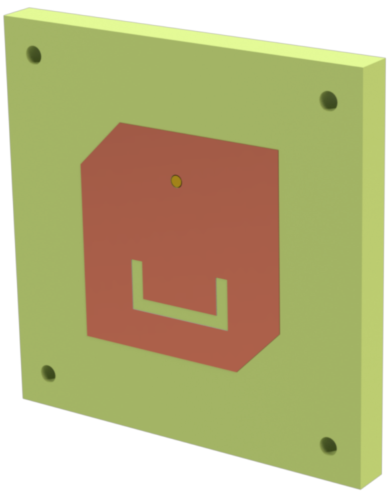

Figure 4*: Patch Antenna render*

2.2.2 UHF Dipole antenna

A custom-made, deployable, omni-directional dipole antenna is employed. The reason for using this type of antenna is to ensure TM & TC reliability in most spacecraft orientations for the UHF links. As simulated in [AD4], the antenna has a theoretical gain of 2.64 dBi and a HPBW of 72°.

The deployment process of the dipole is expanded upon in *ASAT_DDJF_MCH*.

3 Functional architecture

The TT&C subsystems is responsible for handling the incoming and outcoming signals. This entails the demodulation of the incoming signal, maximizing the reliability of the data by applying error correction techniques and verifying the authenticity of said data. TT&C is also responsible for the reverse process which is conducted during the transmission of information. Additionally, the provision to ensure the successfully delivery of all the transfer frames needs to be included. This is achieved by returning the relevant acknowledgement back to the ground station or satellite upon request.

This section gives insight into the communication protocols utilized by the mission's communication systems, as well as the modulation schemes and the error correction codes implemented on the spacecraft's digital signal processing systems. The aforementioned encoding techniques and Data Link Layer protocols are proposed by the CCSDS and ECSS standards. Additionally, this section provides a general overview on how the TT&C subsystem operates in the various operational modes.

3.1 Packet Structure

Our packets consist of an ASM synchronization header, a primary header based on CCSDS (*CCSDS-132.0-B-2*, *CCSDS-232.0-B-3*), a secondary PUS header (*ECSS-E-ST-70-41C*) and an additional field holding the error correction bits as seen in Tables I to III.

***Table I**: S band TM transmitted codeword*

LDPC Codeword					
ASM synchronization header	CCSDS transfer frame primary header	Space Packet Primary Header	PUS TM packet secondary header	TM data field	Error Correction bits
64 bits	48 bits	40 bits	56 bits	3952 bits	1024 bits

***Table II**: UHF TM transmitted codeword*

Convolutional Codeword					
ASM synchronization header	CCSDS transfer frame primary header	Space Packet Primary Header	PUS TM packet secondary header	TM data field	Error Correction bits
32 bits	48 bits	40 bits	56 bits	3952 bits	4128 bits

***Table III**: UHF band TC transmitted codeword*

BCH Codeword					
ASM synchronization header	CCSDS transfer frame primary header	Space Packet Primary Header	PUS TC packet secondary header	TC data field	BCH bits
32 bits	44 bits	40 bits	21 bits	1-877 bits	24-152 bits

The CCSDS primary header if fully compliant with the aforementioned standards as explained in Section 3.1.1, while the PUS secondary header has been slightly modified. Some constant fields have been left out while the size of others has been reduced as for the headers size to be an integer multiple of a byte. For further details on the modifications, refer to Sections 3.1.3 and 3.1.4

The general overview of the data flow on the CubeSat's TT&C subsystem, regarding the communication protocols which are further described in the next sections is presented in Figure 5.

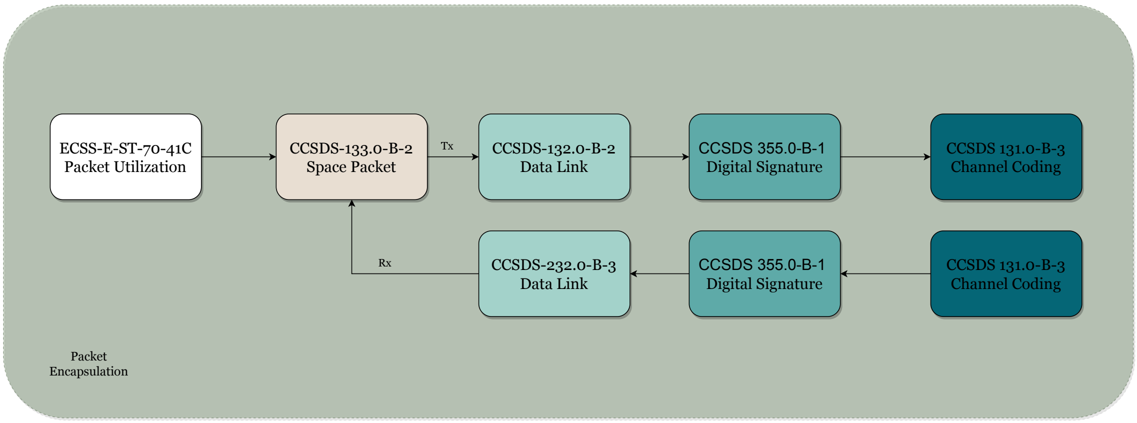

***Figure 5**: Packet Encapsulation Process*

3.1.1 CCSDS Primary Header

Both of the TC (Table IV) and TM (Table V) primary headers are compliant with the referenced CCSDS standards and no further modifications were made.

***Table IV**: CCSDS TC Primary header*

Transfer Frame Version Number	Bypass Flag	Control Command Flag	Reserved Spare	Spacecraft ID	Virtual Channel ID	Frame Length	Frame Sequence Number
enumerated (2 bits)	boolean (1 bit)	boolean (1 bit)	2 bits	enumerated (10 bits)	enumerated (6 bits)	unsigned integer (10 bits)	unsigned integer (8 bits)
2 octets					1 octet		1 octet

Requirements close-out — Review of Design	
The above tables are the close out references for:	
`COMMS-FUN-160`	All payload and TM data units shall carry an identifier that indicates the source spacecraft from which they originate.
`COMMS-FUN-190`	TC data units used shall include a sequence identifier that identifies the data units position in a stream of data units in order to detect duplication or omission of data units.
`GS-FUN-100`	TC data units sent from the ground station shall carry a spacecraft identifier.

3.1.2 Space packet primary header

The space packet protocol is utilized for both the TM and the TC Transfer Frames. The packet structure is fully compatible with the SPP, as it is described in *CCSDS-133.0-B-2*.

***Table V**: CCSDS TM Primary header*

Packet Version Number	Packet ID			Packet Sequence Control		Packet Data Length
	packet type	secondary header flag	application process ID	sequence flags	packet sequence count or packet name	
3 bits	1 bit	1 bit	11 bits	2 bits	14 bits	16 bits
2 octets				2 octets		2 octets

3.1.3 PUS TM Secondary Header

***Table VI**: Modifications to the ECSS TM secondary packet header*

TM packet PUS version number	spacecraft time reference status	message type ID		message type counter	destination ID	time
		service type ID	message subtype ID			
enumerated (4 bits)	enumerated (4 bits)	enumerated (8 bits)	enumerated (8 bits)	unsigned integer (16 8 bits)	enumerated (16 bits)	absolute time
		2 octets		1 octet		4 octets

The TM secondary header is based on the recommendation of *ECSS-E-ST-70-41C* with the deletion of some fields. In more detail:

- The `destinationID` is redundant as the same purpose is also served by the synchronization header and partly the message verification tag.
- `Spacecraft time reference status` is also left out.
- `TM packet PUS version number` has also been removed as it is a constant field.

As *ECSS-E-ST-70-41C* implementations are usually tailored to each specific mission, the impact of minor modifications to the packet structure is not considered harmful to the mission's modularity and operability.

The timestamp format has also been decided to be a modification of the CCSDS Unsegmented Time Code (CUC) format:

- The length of the field is set to **4 bytes**.
- The timestamp will represent the time passed since the 2020-01-01 epoch on **100 ms** intervals.
- The fields will not be range-constrained.

Requirements close-out — Review of Design	
The above text is the close out reference for requirements:	
COMMS-PRA-180	Payload data and TM data units used shall include a sequence identifier that identifies the data units position in a stream of data units in order to detect duplication or omission of data units.
SYS-FUN-260	All TM messages shall include the spacecraft time of their creation.

3.1.4 PUS TC Secondary Header

***Table VII**: Modifications to the ECSS TC secondary packet header*

TC packet PUS version number	response band	acknowledgement flags	message type ID		source ID
			service type ID	message subtype ID	
enumerated (4 bits)	enumerated (1 bit)	enumerated (4 bits)	enumerated (8 bits)	enumerated (8 bits)	enumerated (16 bits)
1 octet			2 octets		

The most important modification of the TC Secondary Header is the addition of the `response band` bit. This bit will determine which band (UHF/S band) will be used to downlink the response to the TC. We also considered the option of setting it by a separate TC but the operational cost was deemed too high. The option of using the MAP ID field of the segment header was also discarded as this was considered too complex.

Again, some fields were removed:

- TM packet PUS version number has also been removed as it is constant.
- The source ID has been removed since it's already included in the CCSDS primary header.

The ACK flag is set by the operator for each TC and determines the type of acknowledgement flag to be sent as in *ECSS-E-ST-70-41C*. In more detail:

- bit 0: acknowledges completion whether the execution of the TC was successful or not.
- bit 1: acknowledges the progress of execution.
- bit 2: acknowledges that execution has started.
- bit 3: acknowledges that the corresponding packet has been accepted by the application process.

Requirements close-out — Review of Design	
The above text is the close out reference for requirement:	
COMMS-FUN-150	COMMS shall enable TC acknowledgements to be returned to the TC source.

3.2 Encoding Schemes

For the UHF communication links, both the TC and TM, follow the GMSK modulation recommended by *CCSDS-401.0-B-29-S* and implementation of *CCSDS-413.0-G-3*. Those modulations are optimized for minimum bandwidth usage. For the S-band payload data, the chosen modulation scheme is OQPSK modulation, which also follows the implementation of the aforementioned standards. Figures 6 and 7 represent the simulated baseband bandwidth of the GMSK and the OQPSK modulation schemes that are described in the two previous standards, when the data rate is 20 kbps and 205 kbps respectively. These values where derived from the *ASAT_DDJF_LINK_ARPT*, as it is found that we have a reliable link and we can downlink all the payload data in a given time frame with these rates.

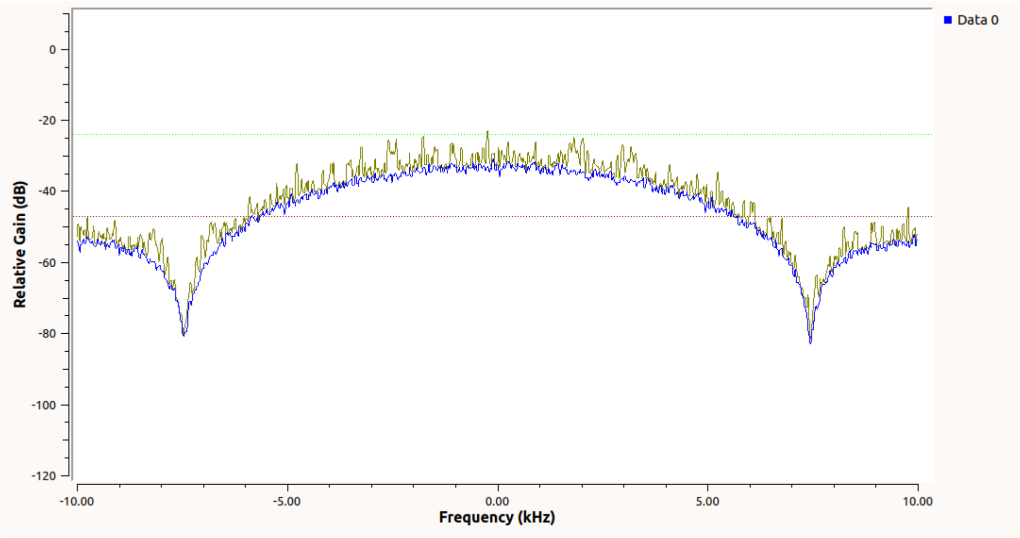

Figure 6: *GMSK plot, BT = 0.5, 20 kbps*

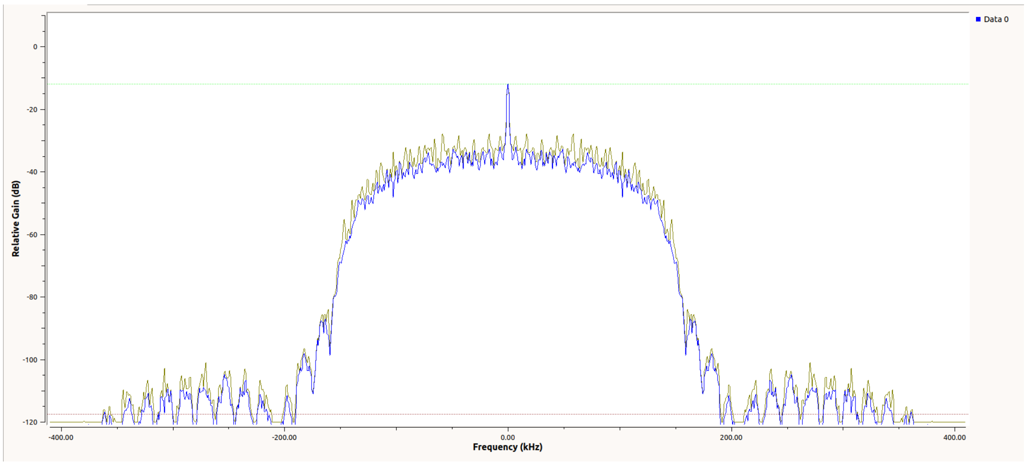

Figure 7: *OQPSK FFT plot, 205 kbps*

In conclusion, while using the previous settings for our signals, a 15 kHz is enough for the UHF transmissions and a 400 kHz for the S-band transmissions.

As the link budget was calculated with the maximum margins it is possible that we may be able to configure the COMMS board at even higher rates. Thus the bandwidth in which the AcubeSAT mission operates is 20 kHz for the UHF, which is the maximum data rate allowed in this spectrum region and 1 MHz for the S-band which allows us to configure the data rate up to approximately 500 kbps.

Requirements close-out — Analysis			
The above figures are the close out references for:			
GS-FUN-010	The ground station shall operate on the radio-amateur band 435-438 MHz (Ultra high frequency (UHF) band), with a maximum bandwidth of at least 20 kHz for Telecomands (TC) uplink.	The analysis indicates that we can achieve a bandwidth of less than 20 kHz given a data rate of 20 kbps.	Fig. 6
GS-FUN-020	The ground station shall operate on the radio-amateur band 435-438 MHz (UHF band), with a maximum bandwidth of at least 20 kHz for Telemetry (TM) reception.	The analysis indicates that we can achieve a bandwidth of less than 20 kHz given a data rate of 20 kbps.	Fig. 6
GS-FUN-030	The ground station shall operate on the radio-amateur band 2.4-2.45 GHz (S band), with a maximum bandwidth of 1 MHz (TBC) for Payload data reception.	The analysis indicates that we can achieve a bandwidth of less than 1 MHz given a data rate of 205 kbps.	Fig. 7

Requirements close-out — Review of Design	
The above text is the close out reference for requirements:	
COMMS-FUN-010	COMMS shall operate on the radio-amateur band 435-438 MHz (UHF band), with a maximum bandwidth of 20 kHz for Telecomands (TC) reception.
COMMS-FUN-020	COMMS shall operate on the radio-amateur band 435-438 MHz (UHF band), with a maximum bandwidth of 20 kHz for Telemetry (TM) downlink.
COMMS-FUN-030	COMMS shall operate on the radio-amateur band 2.4-2.45 GHz (S-band), with a maximum bandwidth of 1 MHz (TBC) for Payload Data downlink.

3.3 Error Correction

As an error correction technique for TC packets, BCH(63, 56) is applied. For the S band payload data TM, the chosen error correction technique is LDPC with a rate of 4/5 and for the UHF TM data the chosen error correction technique is convolutional coding $R = \frac{1}{2}$. Both techniques are recommended by *CCSDS-131.0-B-3*.

LDPC codes were chosen as they are efficient, capacity-approaching codes and an encoder has already been implemented. BCH was chosen for TC since LDPC decoders are more slow and complex. Another reason for choosing BCH is the fact that OBC has a ready implementation.

The maximum allowable BER for both TC and TM packets is 10^{-6} (as per ***COMMS-FUN-080***, ***COMMS-FUN-90*** and ***COMMS-FUN-100***). For TC packets, the FECF is utilized to achieve even lower error rate.

3.4 Message Authentication

40-bit HMAC tags are used for message authentication to ensure that the source is authorized (i.e. our ground station). There will be an option for radio-amateurs to send specific TCs without a MAC tag through dedicated virtual channels.

Requirements close-out — Review of Design	
The above text is the close out reference for requirement:	
COMMS-FUN-110	COMMS shall enable all digitally signed TC packets to be decoded.

***Table VIII**: Probability of forging a 40-bit HMAC tag*

Probability of Success	Expected Time (continuous attack)	Expected Time (limited time window)
1%	153.7 months	25359.1 months
10%	1611.2 months	265847.1 months
50%	10599.7 months	1748958.5 months
90%	35211.6 months	5809914.4 months

Table VIII demonstrates that the chance of guessing a 40-bit HMAC tag is really insignificant. The first column of the table details the expected time of cracking the HMAC given the attacker has continuous contact with the spacecraft (assuming a 681 bit packet size). The second column assumes that the attacker only has a 4 min contact with the satellite per 11 hour pass.

Requirements close-out — Review of Design	
The above section is the close out reference for requirements:	
GS-FUN-090	All TC data units sent from the ground station shall be digitally signed.
SYS-FUN-120	The spacecraft shall not execute TC from unauthorized ground stations.

3.5 Alternative Communication Protocols

Due to high power consumption, the minimization of the FPGA's functionality was taken into consideration. The proposed solution was to utilize the IEEE Std 802.15.4gTM-2012 encoding and modulation schemes which are inherent in the AT86RF215 transceiver. The two main specifications of this standard that we were interested in, are the MR-FSK PHY and the MR-OQPSK PHY, as well as the MAC functionality supported by the transceiver.

While conducting this mitigation strategy analysis, we encountered some unsurpassed problems. The main issue is that the IEEE protocol does not support the 420–450 MHz radiofrequency band. Ultimately, this specification does not permit the usage of the 437 MHz center frequency that we have considered for the TM and TC exchange. Moreover, the FPGA would still have to be functional, as the AT86RF215 does not support the CW modulation scheme.

As a conclusion, the only communication scenario that can be achieved with these protocols is through the S-band. The CubeSat mission is not reliable though without the non-directional UHF dipole, as the link margin is susceptible to changes in the pointing of the spacecraft. Therefore, the mitigation to these protocols is non-feasible, thus there is no plan to use packets, other than those analyzed in the previous sections.

3.6 Functionality

The TT&C subsystem is responsible for processing, generating and distributing TC packets to the other subsystems. It is also responsible for gathering the payload data from SU, generating response TM and successfully transmitting it to the GS.

We need to rely on an agile architecture to allow for more complex yet necessary functionality such as the ability to handle a large volume of data, guarantee the security of the system and implement TCs that can be instantly executed. This section offers a general overview of the basic functions that guarantee that our system is flexible enough to handle a wide variety of edge-cases.

Moreover, the inclusion of various operational modes introduces the need for our system to adjust to the specific conditions of each case. In the following section, we take a deeper look into both the distinct operational and functional aspects of each mode.

3.6.1 Erroneous Telecommands

Invalid TCs are outright rejected by the COMMS Board and an event report is generated in the following cases:

- The `Application process ID` is unknown.
- The `Spacecraft ID` is false.
- The `HMAC` tag is false.
- The packet couldn't be parsed.

3.6.2 High Priority Telecommands

The commands that are marked as High Priority have their Bypass Flag set to 1. This means that the specific packet is of Type-B and will be able to bypass the FARM checks described in *CCSDS-232.1-B-2*.

In the same standard, it is also defined that High Priority Telecommands (HPT) will have their `Sequence Counter` field set to 0. That could raise an issue with HMAC since this implies that a potential adversary could simply resend the same TC without needing to generate a new tag for a packet with an incremented sequence counter. However, considering that the event of sending HPT is rare and the probability of a third party intercepting our packets is really small in the first place, this isn't a need for concern.

3.6.3 Critical Telecommands

Critical telecommands are those that pertain to vital parts of the mission (beginning/stopping the experiment, cessation of transmission etc).

Some of the most critical TCs need to be executed in two steps: One "ARM" TC and a second one that actually executes the command. The ARM TC will be disregarded in case the second TC is invalid, namely:

- The HMAC tag is invalid.
- The ARM command exceeded the execution timeframe.
- The sequence counter difference between the two packets exceeded the set threshold.

The exact thresholds are yet to be defined as of September 2020. We expect to determine the most effective values in the testing phase.

Specifically, for checking the frame sequence counter, a FARM sliding window as specified in *CCSDS-231.0-B-2-S* is used. In more detail, this structure allows us to accept a transfer frame if the difference is minimal, discard it and possibly re-transmit any frames stored in the queue of sent TCs or discard the frame and enter the *lockout* stage if the difference between the expected sequence number and the actual sequence number of the received transfer frame is too big. While in *lockout* stage, the satellite won't be able to accept or transmit any Type-A Frame Data Units (FDUs) until the respective *unlock* TC is received.

3.6.4 Congestion

To avoid congestion, a circular buffer is utilized in which the telecommands are being stored when the quantity of functions exceeds the operational capacity of the CubeSat. If the buffer is full, newly received non-critical commands are discarded. In case a critical TC arrives and the buffer is full, the last Transfer Frame in the buffer will be overwritten. For a more comprehensive overview of the process refer to *CCSDS-232.1-B-2*.

3.6.5 Commanding-in-the-blind

Commanding-in-the-blind refers to sending TCs in the absence of any response from the satellite either in the form of feedback TM or an acknowledgement.

The operator can send TCs despite of the lack of relevant feedback. A detailed report from all previous requests which are saved at the packet stores as explained in the *ASAT_MDO* can be provided after a prompt from an appropriate TC.

Regarding the acknowledgement of successful execution of TCs, this is determined by the acknowledgement flags set by the operator which are described in detail in Section 3.1.4. This way, an operator can make sure of a successful execution of a TC even when the expected TM data hasn't been received.

In the absence of any relevant feedback from the satellite, the operator attempts first attempts to request the TM response from the UHF. If the problem persists, they attempt to reset the satellite when it is expected to pass above the GS.

3.6.6 Cessation of emissions

The operator can manually send a TC to terminate the transmission in the UHF and/or S band. Subsequent TCs that expect a TM response should set their `response band` bit accordingly as described in Section 3.7.4.

Restart of TX operations can commence when a specific TC is sent, which can be received in-the-blind by the spacecraft.

3.6.7 Telemetry-in-the-blind

Telemetry-in-the-blind applies to the acquisition of telemetry data without any prompt from the GS. In our design, the only such way this can be achieved is through the beacons that are emitted in regular intervals.

The payload data can only be downlinked after the corresponding TC has been sent. In the UHF, TM can either be downlinked as a response to a TC sent from the GS or through the GMSK and CW beacons that are emitted in fixed intervals.

The GMSK beacon is automatically transmitted every 1 minute regardless of the position of the satellite. All other TM reports are also transmitted the exact moment they're generated. This functionality allows the use of the *SatNOGS* network as well as the participation of the radio-amateur community in decoding the transmitted satellite state, offering precious insight to the team, especially during the LEOP phase.

On top of the above, the operator is also able to request all produced reports within a given timeframe. This way, in the beginning of each pass, the operator can downlink all event reports that were generated while AcubeSAT was out of the line of sight of the GS.

An additional CW beacon is also utilized to monitor the most vital parameters of *AcubeSAT*. The CW beacon is modulated as OOK Morse Code, has a rate of 20 WPM and its duration is approximately 9.6 seconds. Every parameter of the CW is coded as a letter from A-Z, indicating the range of values in which the parameter lies or the exact value of the parameter. The rationale behind the CW beacon is inspired by UPSat's CW.Additionally, the CW beacon is easily decoded by the radio amateur community and permits the identification of the spacecraft during contingency situations such as the first contact with our GS or any other receiver after launch.

Due to power constraints and the significant duration of the beacon, it is emitted every

5 minutes by default. Note that we are planning to map the most frequently occurring values (e.g. operational temperatures) to letters that have a shorter transmission time (e.g. E, I, T) in an effort to lower the expected duration of the beacon.

The sequence of the emitted beacons is described below. There is a one-minute interval between each beacon:

- GMSK
- GMSK
- CW
- GMSK
- GMSK

Since a beacon is emitted every minute, there is a big possibility that at least one of them is received in each pass. Due to the sampling frequency of the parameters included in the beacons, which is 30 seconds, the values of the parameters will be different in each beacon, providing extra information to the operator.

The exact parameters included in the CW beacon can be seen in Table IX. For a full list of the parameters included in each beacon refer to *ASAT_MDO*.

***Table IX**: CW beacon*

A	S	A	T	Parameter	Battery Voltage	Total Subsystem Current	Total Panel Voltage	RSSI	UHF band PA temperature	S band PA temperature	Command Counter	Payload Chip Temperature	Current mode	Last Event
x	x	x	x	Unit	V	I	V	dBm	°C	°C	-	°C	-	-

Requirements close-out — Review of Design	
The above text is the close out reference for requirement:	
COMMS-OPS-170	S-band Payload data shall be transmitted towards the Earth only when the spacecraft passes over a compatible ground station.

3.6.8 Commandability at all anticipated attitudes and rates

TCs can be sent to the satellite even when it is tumbling and at all anticipated attitudes. Additionally, UHF telemetry can be sent to the ground station but no experimental payload data can be transmitted during Safe Mode.

3.7 Reception/Transmission in Operational Modes

Depending on the constraints of each mode (i.e. limited power, substantial nadir pointing error, etc) transmission in the S- band may be disabled in certain modes as better illustrated in Table X. However, both UHF Tx and Rx normally operate throughout the whole mission and the operator can act accordingly as to mitigate the impact of having the S band Tx disabled.

***Table X**: UHF/S band operability in operational modes*

	UHF Rx	UHF Tx	S-Band Tx
Comissioning Mode	x	x [1]	
Nominal Mode	x	x	x
Safe Mode	x	x	
Science Mode	x	x	

[1] TX enabled only after the antenna has been successfully deployed

Requirements close-out — Review of Design	
The above text is the close out reference for requirement:	
COMMS-OPS-040	Capability of aquiring and downlinking TM shall be available during all mission modes except Launch Mode.

3.7.1 Commissioning Mode

During **Commissioning Mode**, the deployment of the UHF antenna will take place. The operator won't be able to communicate with the satellite until the deployment has been complete, in which case the satellite will enter **Safe Mode**. In case the deployable antenna has been successfully deployed without the satellite knowing (for example in case of a failure in the deployment detection), the operator will be able to communicate through the UHF as normal and can send the relevant telecommand to manually enter **Safe Mode**.

3.7.2 Nominal Mode

In **Nominal Mode**, both the S-band and the UHF are turned on and the satellite can both receive telecommands and transmit telemetry data. Due to power constraints ([14, Section 3]), the S band and UHF Tx will not be operating simultaneously.

3.7.3 Science Mode

During **Science Mode**, the S band remains turned off throughout the duration of the mode so as to not consume additional power. However, there will be an option for the operator to request part of the image through the UHF to ensure that images are generated properly.

3.7.4 Safe Mode

Transmission in S-band is disabled during **Safe Mode** and Science mode. There is the option to have the satellite transmit the payload data in the UHF instead of the S band if the `response band` bit in the primary header is set to 1. In case the `response band` bit is set to 1 during Safe mode or Science mode, a rejection message will be sent back.

3.8 Watchdogs

A **recovery countdown timer** is responsible for resetting the SC to a previously known state if no TC is received for a set time frame [15, 3.1 Functional Architecture]. This is implemented by a timer that resets each time the operator manually confirms the current configuration of the satellite as being safe. If no such commands are received over a large time interval, the configuration and the satellite return to their *launch* state while the software itself doesn't automatically revert back to its unpatched version. If the problem persists after the reset and no contact can be established for an extended period of time, the satellite automatically enters **Safe Mode**.

For further details you can refer to [16, 4.3 On-board reconfiguration timer].

4 Link and Data Budget Summary

A static and a dynamic Link and Data Budget analyses were conducted for the AcubeSAT mission, which are found in *ASAT_DDJF_LINK_ARPT*. We have considered that the communications window for the UHF link (Telemetry Data) starts from 20 degrees elevation angle while the communication window for the S-band link (Payload Data) starts from 30 degrees elevation angle.

The losses on both the Spacecraft's and the Ground Station's equipment where taken into account as well as the FSPL, the atmospheric losses and a pointing loss of 15 degrees from the ADCS nadir pointing of the patch antenna. The required BER for all links is 10^{-6} and the required data rate is considered to be 20 kbps and 205 kbps for the UHF downlink/uplink and the S band downlink respectively. The data budgets indicate that all payload data can be successfully downlinked during our mission's lifetime.

A common threshold for the reliability of the link margin is at 10 dB. This isn't achieved for all links in **Nominal Mode**: S Band Downlink (8.8 dB), UHF Uplink (17.2 dB) and UHF Downlink (7.0 dB), but an initial analysis has resulted in 4.0 dB for the UHF Downlink in Safe/Science Mode. It needs to be noted that for the above margins the absolute worst pointing error was considered and are not a general indication of the typical link margin of each scenario.