CuPID Communications Systems Description Document

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Revision History

REV.	Description of Change	Effective Date
Rev1	Release	9/15/2017
Rev2	Adding Requested FCC data for satellite orbit and transmitter and receiver technical details and location	9/19/2017
Rev3	Update antenna gains, link budgets, and emission designators	7/18/2018

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1. INTRODUCTION

1.1 Background and Purpose

The Cusp Plasma Imaging Detector (CuPID) satellite provides a soft X-ray imager platform in Low Earth Orbit (LEO). The project is run by Boston University, Department of Engineering who will be the Principal Investigators.

The flight program is based on a 6U formfactor small satellite. Placed in a high inclination (>65 degrees) circular orbit, the satellite is flown at a 500 km altitude. The satellite gathers experimental data and receives commands through an Ultra-High Frequency (UHF) communications system. The mission life is 3 months minimum (requirement) and 1 year desired.

The CuPID end-to-end communications system is shown in Figure 1, including both the spacecraft and ground station systems. The radio link operates in the UHF band with a proposed Federal Communications Commission (FCC) allocation in the 400-405 MHz band.

The radio link operates in half-duplex, that is, it cycles between transmit and receive as required. Therefore, it cannot transmit and receive at the same time. The radio transmits and receives through a Dipole antenna that is deployed after launch. The Dipole provides a linear radiation pattern around the spacecraft.

The communications subsystem has both physical and over-air interfaces. The physical interfaces for the radio on the spacecraft consist of radio control and monitoring, telemetry transmission, and command reception. Over those interfaces, various controls are established and data can be sent and received. This document describes the communications subsystem, the associated interfaces, and the format and type of data that flows over them.

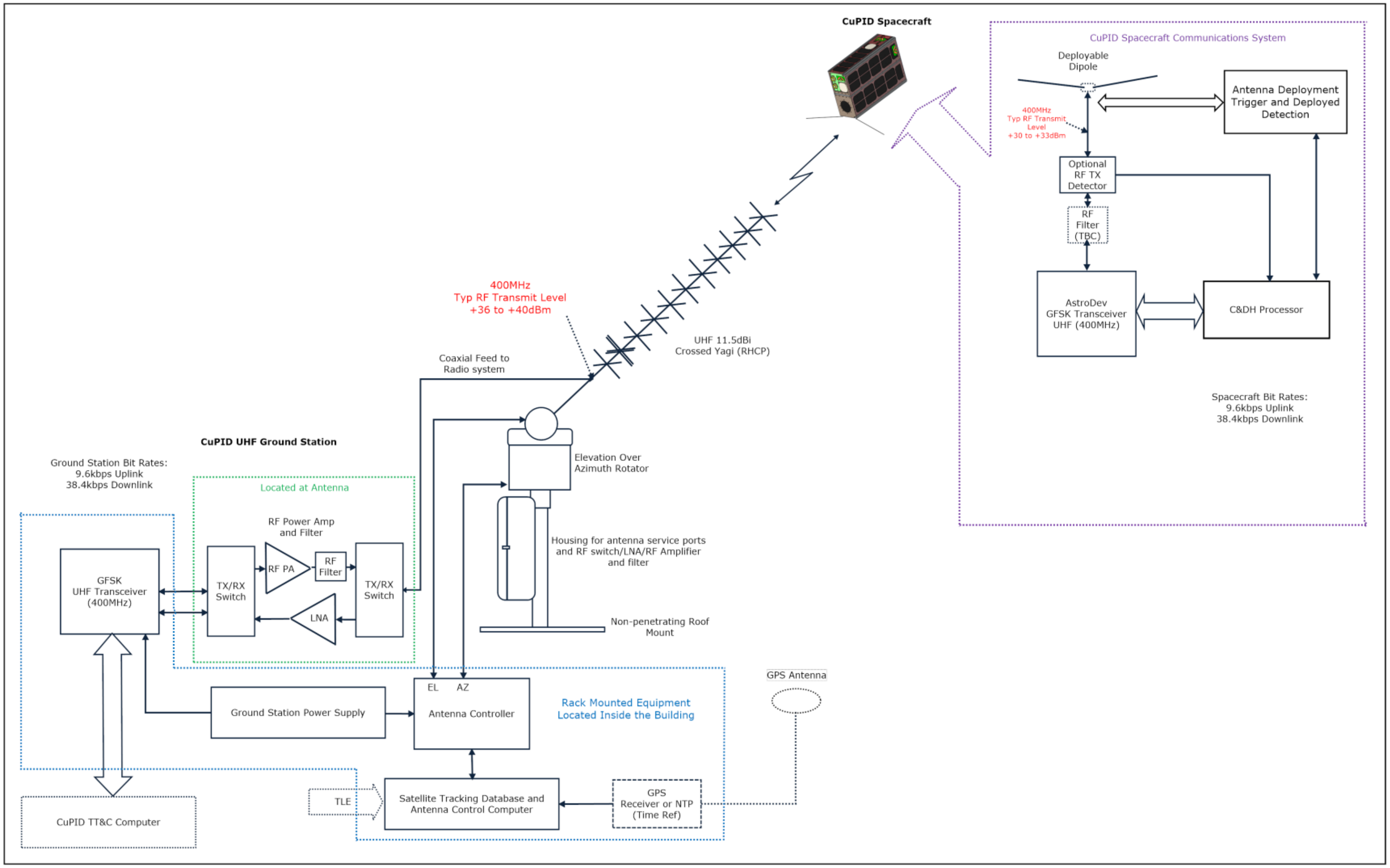

Figure 1: CuPID End-to-End Communications System

1.2 Scope

This document describes the CuPID space-to-ground and ground-to-space communications links, the technical parameters, and radio link requirements. This includes the radio over-air interface, the hardware implementation, and the data bit rates.

1.3 ACRONYMS AND ABBREVIATIONS

A	Amperes
AFSK	Audio Frequency Shift Keying
AGC	Automatic Gain Control
AOS	Acquisition of Signal
BER	Bit Error Rate
BOL	Beginning-of-life
bps	Bits per second
BPSK	Binary Phase Shift Keying
BT	Bandwidth Time Product
BW	Bandwidth
CDI	Command and Data Interface
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CuPID	Cusp Plasma Imaging Detector
dB	Decibel
dBc	Decibel referenced to carrier
dBi	Decibel referenced to Isotropic Antenna Gain
dBd	Decibel referenced to Dipole Antenna Gain
dBm	Decibel referenced to 1 milliwatt
dBW	Decibel referenced to 1 Watt
DC	Direct Current
D_R	Doppler Range
D_{Ra}	Doppler Rate in Hz/sec
EIRP	Effective Isotropic Radiated Power
EMC	Electromagnetic compatibility
EOL	End-of-life
FCC	Federal Communications Commission
FEC	Forward Error Correction
FIFO	First-in First-out
F_R	Receiver center frequency
F_T	Transmitter center frequency
GFSK	Gaussian Frequency Shift Keying
GHz	Frequency in Gigahertz, 10^9 hertz
GSE	Ground Support Equipment
HPA	High Power Amplifier
Hz	Hertz
ICD	Interface Control Drawing
I&T	Integration and Test
JTAG	Joint Test Action Group
K	Kelvin
kbps	Kilobits per second
kg	Kilogram, 10^3 grams
kHz	Kilohertz, 10^3 hertz

kRads	Kilo-Rads
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
LOS	Loss of Signal
Mbps	Megabits per second
MHz	Megahertz, 10^6 hertz
ms	Millisecond, 10^{-3} second
MSB	Most Significant Byte
PCB	Printed Circuit Board
PER	Packet Error Rate
ppm	Parts per million
QFH	Quadrafiliar Helix Antenna
RF	Radio Frequency
SEB	Single Event Burnout
SEE	Single Event Effects
SEGR	Single Event Gate Rupture
SEL	Single Event Latchup
TBC	To Be Confirmed
TBD	To Be Determined
UART	Universal Asynchronous Receiver/Transmitter
UHF	Ultra-High Frequency
µs	Micro-second, 10^{-6} second
V	Volts
VAC	Voltage, alternating current
VDC	Voltage, direct current
VSWR	Voltage Standing Wave Ratio
W	Watts

1.4 Reference Documents

Item	Title	Release	Source
1	NTIA Red Book	9/15	NTIA
2	FCC Title 47 CFR	9/13/17	FCC
3	NASA SNUG, Rev 10	8/3/12	NASA

2. Communications Radio Module Interfaces

2.1 CuPID Spacecraft High Level Specifications

Parameter	Specification
Altitude	500km
Dimensions	6U
Mass	TBC
Operating Voltage	12VDC Nominal
Max Power	TBC
Orbit Life	3 Months Required, 1 Year Desired

Table 1: CuPID Spacecraft High-level Specification

2.2 CuPID Radio Subsystem

CuPID uses the AstroDev Li-2 radio module to provide the RF link between the spacecraft and the ground station. It consists of a half-duplex transceiver housed in a single module housing.

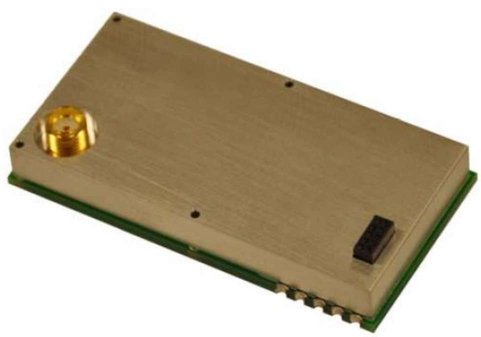

Figure 2: AstroDev Li-2 Transceiver Module

This module provides a UHF transceiver that can operate between 400MHz and 450MHz. Gaussian Frequency Shift Keying (GFSK) and Binary Phase Shift Keying (BPSK) modulation schemes are available with bit rates of 9.6 kbps and 38.4 kbps. The absolute maximum ratings for the transceiver are shown in Table 2.

Interface Parameter	Symbol	Min.	Typ.	Max.	Units
Operating temperature	T_{OP}	-30.0 to +70.0			°C
DC Radio Voltage	V_{amp}	6.0		13.0	V
DC Radio Current	I_{amp}	0.02		2.0	A

Table 2: Li-2 Module Absolute Maximum Ratings

2.3 Li-2 Mechanical Interface

The Li-2 transceiver module is surfaced mounted with a top enclosure. It has physical connectors and solder interfaces on the top side of the module. The dimensions are listed in Table 3 below. Note that the module which will be used for the CuPID spacecraft will use an MCX RF connector in place of the SMA connector shown in Figure 3 below. The MCX connector will be centered on the SMA connector footprint.

2.3.1 Physical Characteristics

The transceiver module is a single enclosure that is surface mounted onto a host Printed Circuit Board (PCB).

Physical Parameter	Symbol	Min.	Typ.	Max.	Units
Mass	M	30		52	g
Height	H	0.0		11.12	mm
Width	W		32	33	mm
Length	L		64	65	mm

Table 3: Physical Parameters

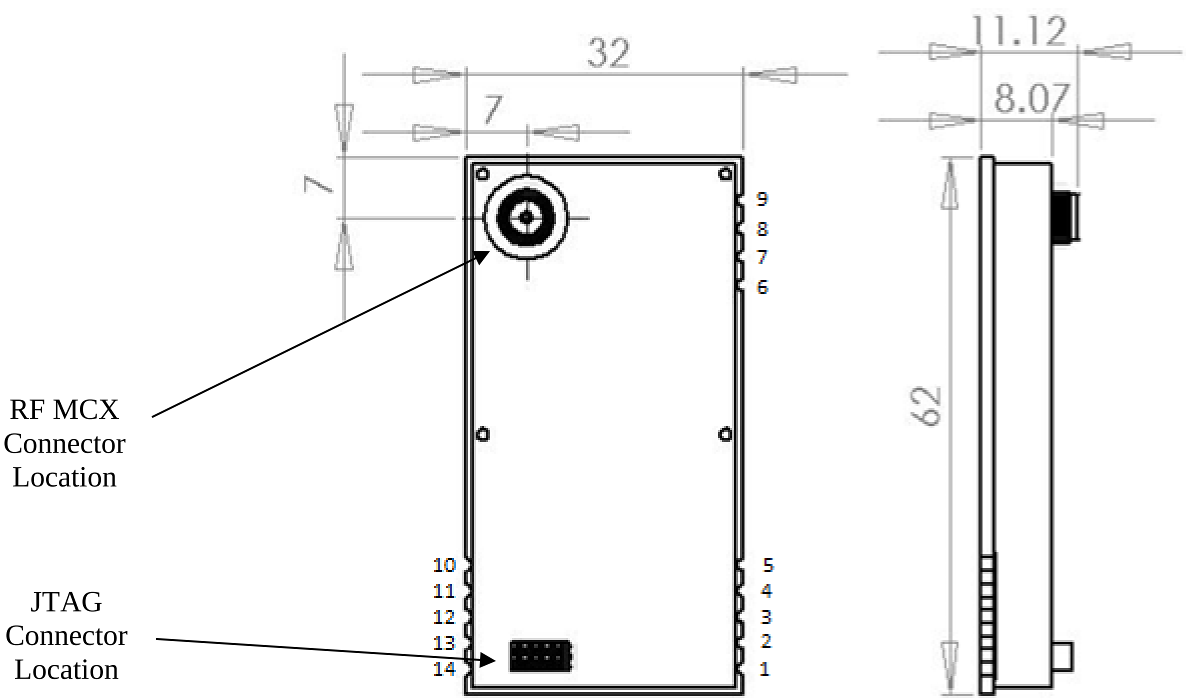

Figure 3: AstroDev Li-2 Transceiver Module (all dimensions are in mm)

The RF limits for the transceiver transmitter output are shown in Table 4.

Physical Parameter	Min.	Typ.	Max.	Units
RF Output	-70		+38	dBm

Table 4: RF Output Limits

2.3.2 Li-2 Serial Data Interfaces

A digital command and data interface is provided to the radio. Through this interface, the radio is configured, uplink data is received, and downlink data is sent for transmission. The interface protocol is serial UART and configurable at up to 115.2 kbps. A packet protocol with checksums is implemented between the host and radio for robust access. Also, a standard serial programming JTAG interface is provided. This enables the radio firmware to be updated through this serial interface.

2.3.2.1 Data Protocol Description

Li-2 radios support a subset of the AX.25 packet radio protocol as defined by https://www.tapr.org/pub_ax25.html. Only the handling of Ul frames is implemented, not full connected mode. Users can configure the source and destination call signs, the packet length, and the TX tail and head parameter. The radio performs all packetization functions such as bit stuffing and checksum calculations.

2.3.2.2 Transmit Overview

Radio transmissions are performed based on the radio mode setting. All data received from the hardware interface is immediately transmitted unless the radio is busy with a current transmission. Data to be transmitted will be temporarily retained in the transmission buffer based upon the RF baud rate and the buffer length.

During transmission, the radio uses a Command and Data Interface (CDI). The parameters over this interface default to standard AX.25 settings.

2.3.2.3 Receive Overview

Radio receive operations are performed based on the radio mode setting and hardware interface method. During reception, the radio maintains the interface through the Command and Data. The parameters default to standard AX.25 settings.

2.3.2.4 Data Rates

This section provides an overview of the data rate used during the CuPID mission. The data rate settings of the radio are specific to the hardware type and are set at manufacture. Increasing data rate uses different filter, modulation, and power settings for communications can be achieved only with configuration changers and/or firmware updates. Each data rate used on CuPID is described below:

9.6 kbps GFSK: Standard AX.25 data rate (CuPID uplink bit rate)

38.4 kbps GFSK: Higher speed GFSK modulation (CuPID Downlink bit rate)

3. Spacecraft Antenna

The CuPID satellite maintains contact with the ground via the commercial UHF spectrum. This requires a UHF Dipole antenna, with 2.15 dBi gain, that is deployable from the spacecraft once in orbit. The Dipole antenna consists of two elements fed from a coaxial cable that is directly connected to the Radio.

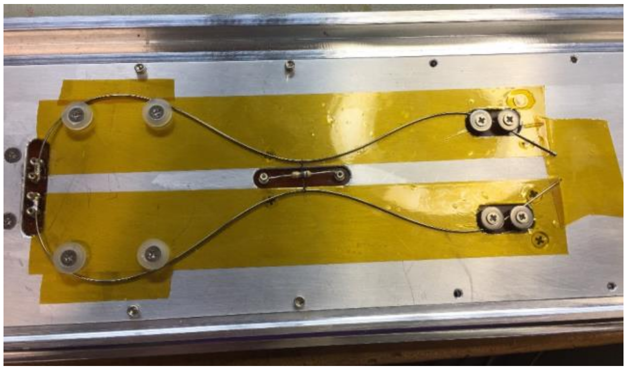

Figure 4: Stowed CuPID Antenna (Prototype)

The antenna is stowed on a 1U x 3U panel against the spacecraft body during launch. Once in orbit, a release command is sent and the antenna is deployed.

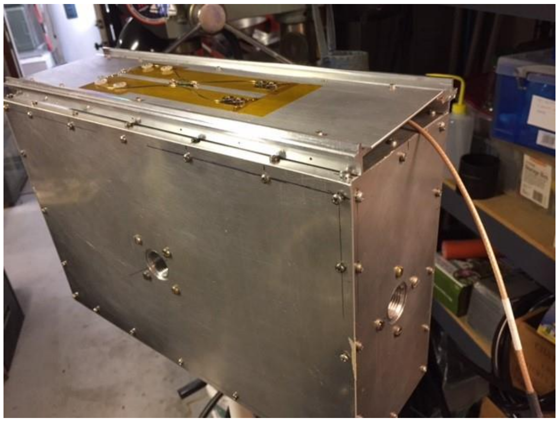

Figure 5: Antenna Test Model on a 6U Spacecraft Body Model

3.1 RF Interface Impedance Matching

The antenna is optimized for a single frequency due to the use of half-duplex communications. This match ensures the maximum efficiency of the antenna when in the deployed configuration.
The antenna interface, when measured through the attached coaxial cable, shall provide a match that is better than 1.4:1 VSWR (>15.5dB Return loss). The measurement at this interface shall be verified using a Vector Network Analyzer and a Smith chart plot shall be provided as verification of the antenna impedance match.

4. Radio Link Interface

The communications subsystem supports a half-duplex UHF radio link for the command uplink and telemetry downlink. The frequency allocation will be determined as part of the radio licensing process. However, it is expected that this will be within the 400-405MHz UHF spectrum.

The radio is based on the AstroDev Li-2 module. This a self-contained, surface mounted transceiver that is connected to a Dipole antenna. The Dipole is stowed during launch and deployed on command once on orbit. It consists of two elements set in a slight 'V' shape to provide an efficient match to the transmitter and receiver.

The radio module is capable of providing a transmitter RF carrier level of up to 7 Watts. However, as shown in the link budgets in this document, the transmitter power will be set to 1 Watt during the CuPID mission. The RF power setting of 1 Watt is hard-coded into the spacecraft firmware and cannot be changed once set and the spacecraft is in orbit. The RF link parameters are shown in Table 5.

Parameter	Specification
Frequency	400 to 405MHz
DL TX Antenna Gain	2.15 dBi
DL TX Antenna Polarization	Linear
DL TX RF Power	1 Watt
DL TX EIRP	28.85 dBmW
Transmission Configuration	Half-duplex
Modulation	Gaussian Frequency Shift Keying (GFSK)
Uplink Bit Rate	9.6 kbps
Necessary Bandwidth (Bn)	13.44 kHz
FCC Emission Designator	13K4F1D
Downlink Bit Rate	38.4 kbps
Necessary Bandwidth (Bn)	53.76 kHz
FCC Emission Designator	53K7F1D

Table 5: Radio Link Interface Parameters

The over-air interface, through the radio link, provides a data link in the uplink and downlink paths with a $1x\ 10^{-5}$ Bit Error Rate. The link budget analyses in Table 6 and Table 7 show details of the radio link performance using the AstroDev Li-2 transceiver and the deployable Dipole antenna on the CuPID spacecraft. This link analysis also uses the ground station antenna interface, its associated antenna gain, and resulting G/T performance to derive the link margins that will be realized with CuPID in a 500 km orbit (will be updated when launch is assigned and final orbit altitude is confirmed). The ground station over-air interface and the required performance are discussed in the Ground Station Interface description in Section 5.

		5 Watt TX - Ground Station Uplink			
		Earth Station Elevation Above Local Horizon			
Parameters	**Units**	**90°**	**40°**	**10°**	**5°**
Frequency	MHz	400.5			
Wavelength	m	0.75			
Data Rate	kbps	9.6	9.6	9.6	9.6
Earth Radius	km	6378.14	6378.14	6378.14	6378.14
Symbol Rate	ksps	9.6	9.6	9.6	9.6
Elevation Angle	degrees	90	40	10	5
Spacecraft Orbital Altitude	km	500	500	500	500
Angular Radius of Earth	degrees	68.02	68.02	68.02	68.02
Nadir Angle	degrees	0.00	45.26	65.95	67.48
Earth Central Angle	degrees	0.00	4.74	14.05	17.52
Range	km	500.00	741.33	1695.09	2077.96
Transmit Parameters					
Transmitter Power	dBm	36.99	36.99	36.99	36.99
Transmitter Network Loss	dB	-1.50	-1.50	-1.50	-1.50
Earth Station Antenna Cross Pol Loss	dB	-3.00	-3.00	-3.00	-3.00
Earth Station Antenna Gain	dBi	14.35	14.35	14.35	14.35
EIRP	dBm	46.84	46.84	46.84	46.84
Channel Parameters					
Space Path Loss	dB	-138.48	-141.90	-149.08	-150.85
Atmospheric and Scintillation Loss	dB	0.00	-0.21	-0.41	-0.41
Rain Loss	dB	0.00	-0.09	-0.18	-0.18
Polarization Loss	dB	-0.25	-0.25	-0.25	-0.25
Receiver Parameters					
Spacecraft Receiver G/T	dB/K	-27.00	-28.80	-32.20	-32.70
Power Summary					
Received Power at Antenna input	dBm	-91.89	-95.61	-103.08	-104.85
Boltzmann's Constant	dB	-228.60	-228.60	-228.60	-228.60
C/No at spacecraft	dB-Hz	79.71	74.19	63.32	61.05
BER 1e-05					
C/No	dB-Hz	79.71	74.19	63.32	61.05
Bit Rate	bps	9600	9600	9600	9600
Occupied Bandwidth	dB-Hz	39.82	39.82	39.82	39.82
Received Eb/No	dB	39.89	34.37	23.49	21.23
Demod Implementation Loss	dB	-1.40	-1.40	-1.40	-1.40
FEC Coding Gain	dB	0.00	0.00	0.00	0.00
Resulting Eb/No	dB	38.49	32.97	22.09	19.83
Theoretical Eb/No (Measured)	dB	10.10	10.10	10.10	10.10
BER margin	**dB**	**28.39**	**22.87**	**11.99**	**9.73**

Table 6: Uplink Link Budget Analysis

		1 Watt TX - Downlink to Ground Station			
		Earth Station Elevation Above Horizon			
Parameters	**Units**	**90°**	**40°**	**10°**	**5°**
Frequency	MHz	400.5			
Wavelength	m	0.75			
Data Rate	kbps	38.4	38.4	38.4	38.4
Earth Radius	km	6378.14	6378.14	6378.14	6378.14
Symbol Rate	ksps	38.4	38.4	38.4	38.4
Elevation Angle	degrees	90	40	10	5
Spacecraft Orbital Altitude	km	500	500	500	500
Angular Radius of Earth	degrees	68.02	68.02	68.02	68.02
Nadir Angle	degrees	0.00	45.26	65.95	67.48
Earth Central Angle	degrees	0.00	4.74	14.05	17.52
Range	km	500.00	741.33	1695.09	2077.96
Transmit Parameters					
Transmitter Power	dBm	30.00	30.00	30.00	30.00
Transmitter Network Loss	dB	-3.30	-3.30	-3.30	-3.30
Spacecraft Antenna Gain	dBi	2.15	2.15	2.15	2.15
EIRP	dBm	28.85	28.85	28.85	28.85
Channel Parameters					
Space Path Loss	dB	-138.48	-141.90	-149.08	-150.85
Atmospheric and Scintillation Loss	dB	0.00	-0.21	-0.41	-0.41
Rain Loss	dB	0.00	-0.09	-0.18	-0.18
Earth Station Antenna Cross Pol Loss	dB	-3.00	-3.00	-3.00	-3.00
Polarization Loss	dB	-0.25	-0.25	-0.25	-0.25
Receiver Parameters					
Ground Station Receiver G/T	dB/K	-8.46	-8.58	-8.87	-9.25
Power Summary					
Received Power at Ground Station input	dBm	-112.88	-116.60	-124.07	-125.84
Boltzmann's Constant	dB	-228.60	-228.60	-228.60	-228.60
C/No at Ground Station	dB-Hz	77.26	73.42	65.65	63.51
BER 1e-05					
C/No	dB-Hz	77.26	73.42	65.65	63.51
Bit Rate	bps	38400	38400	38400	38400
Occupied Bandwidth	dB-Hz	45.84	45.84	45.84	45.84
Received Eb/No	dB	31.42	27.58	19.81	17.67
Demod Implementation Loss	dB	-1.40	-1.40	-1.40	-1.40
FEC Coding Gain	dB	5.00	5.00	5.00	5.00
Resulting Eb/No	dB	35.02	31.18	23.41	21.27
Theoretical Eb/No	dB	10.10	10.10	10.10	10.10
BER margin	**dB**	**24.92**	**21.08**	**13.31**	**11.17**

Table 7: Downlink Link Budget Analysis

5. Ground Station Interface

The CuPID ground station can be implemented either using a local ground station at Boston University or with an option to communicate through the NASA Wallops UHF ground station facility. This section discusses the minimum performance requirements of any ground station to meet or exceed the link margins as shown in the link budget analyses in Table 6 and Table 7.

5.1 Ground Station Uplink Interface Requirements

Table 8 shows the minimum requirements for any ground station to be able to support robust uplink communications with CuPID in orbit. This requires a link margin of greater than 3dB above the threshold of the required BER of $1x10^{-5}$.

Parameter	Specification
Frequency	400 to 405MHz
TX Antenna Type (Ground Station)	Tracking Crossed Yagi (360°Az, 180°El)
TX Antenna Gain	14.35 dBi
Antenna HPBW (-3dB)	35.2°
TX Antenna Polarization	Right-hand Circular Polarization
TX RF Power	5 W
TX EIRP	49.84 dBmW
RX Antenna Type (Satellite)	Dipole
RX Antenna Gain	2.15 dBi
RX Antenna Polarization	Linear
Transmission Configuration	Half-Duplex
Modulation	Gaussian Frequency Shift Keying (GFSK)
Bandwidth Time Product (BT)	0.3
Deviation	4.8 kHz
Bit Rate	9.6 kbps
Bandwidth	13.44 kHz
FCC Emission Designator	13K4F1D
Antenna Tracking	Open Loop Tracking

Table 8: Uplink Interface Performance Requirements to Support CuPID On-orbit Operations

5.2 Ground Station Downlink Interface Requirements

Table 9 shows the minimum requirements for any ground station to be able to support robust downlink communications with CuPID in orbit. This requires a link margin of greater than 3dB above the threshold of the required BER of $1x10^{-5}$.

Parameter	Specification
Frequency	400.5 MHz (Used for analysis only, final frequency subject to FCC approval)
TX Antenna Type (Satellite)	Dipole
TX Antenna Gain	2.15 dBi
TX Antenna Polarization	Linear
TX RF Power	1 W
TX EIRP	28.85 dBmW
RX Antenna Type (Ground Station)	Tracking Crossed Yagi (360°Az, 180°El)
RX Antenna Gain	14.35 dBi
RX Antenna Polarization	Right-hand Circular Polarization
Transmission Configuration	Half-Duplex
Modulation	Gaussian Frequency Shift Keying (GFSK)
Bandwidth Time Product (BT)	0.5
Deviation	19.2 kHz
Bit Rate	38.4 kbps
Bandwidth	53.76 kHz
FCC Emission Designator	53K7F1D
Antenna Tracking	Open Loop Tracking

Table 9: Downlink Interface Performance Requirements to Support CuPID On-orbit Operations

The ground station uses the AstroDev Li-2 radio and therefore the interface will be identical to the spacecraft as detailed in Section 2 of this document.

5.3 Transmitter, Receiver and Orbit Summary Details

Transmitter Antenna on The CuPID Spacecraft:

Location: 500km Orbit (Low Earth Orbit)
Apogee and Perigee: 500km, Circular Orbit
Polarization: Linear
Orientation: Horizontal polarization when flying LVLH (Local Vertical Local Horizontal)
Dimension: 17 Inch (Dipole)
Gain (dBi): 2.15dBi
Beamwidth (degree): 180°
(also see Table 9: Downlink Interface Performance Requirements to Support CuPID On-orbit Operations**)**

Ground Station and Antenna:
Location: Boston University, Boston, MA
lat/long: 42° 20’ 56.7”N, 71° 06’ 20.1” W
Polarization: Right Hand Circular
Orientation: Pointing up in the sky!
Dimension: 53 inch Yagi Antenna
Gain (dBi): 14.35dBi
Beamwidth (degree): 35.2° (-3dB)
Azimuth (degree clockwise from True North): 180° tracking Elevation and 360° Azimuth
Elevation (in meter above MSL): 30m
Height of antenna mast: 2m
Ground Station Transmitter: 5 Watts
(Also see Table 8: Uplink Interface Performance Requirements to Support CuPID On-orbit Operations)

Cupid Orbital Characteristics:
Inclination angle (in degree): 80°
Apogee (in km): 500km
Perigee (in km) 500km
Period (in hours): 1.5
Number of satellite in the system: One
Number of transmitting satellite: One
Number of receiving satellite: One