Mit castor satellite: Design, implementation, and testing of the communication system ☆

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ABSTRACT

Cathode Anode Satellite Thruster for Orbital Reposition (CASTOR) is an orbital manoeuvre and transfer micro-satellite bus developed at MIT Space System Laboratory. The technical objective of the mission is achieving 1 km/s of delta-V over a 1 year mission in Low Earth Orbit (LEO). This will be accomplished using a novel electric propulsion system, the Diverging Cusped Field Thruster (DCFT), which enables high efficiency orbital changes of the ESPA-ring class satellite. CASTOR is capable of improving rapid access to space capabilities by providing an orbital transfer platform with a very high performance to mass ratio, thus greatly reducing launch costs and allowing for highly efficient orbital manoeuvre. Furthermore, CASTOR is highly scalable and modular, allowing it to be adapted to a wide range of scales and applications. CASTOR is developed as part of the University Nanosatellite Program (UNP) funded by Air Force Research Laboratory (AFRL).

In order to accomplish CASTOR mission objective, a highly optimized, scalable, light weight, and low cost communication system needed to be developed. These constraints imply the development of trade studies to select the final communication system architecture able to maximize the amount of data transmitted, while guaranteeing reliability, redundancy and limited mass, power consumption, and cost. A special attention is also required to guarantee a reliable communication system in cases of tumbling, or in case of strong Doppler shift which is inevitable due to the high delta-V capabilities of the vehicle. In order to accomplish all the mission requirements, different features have been introduced in the design of the communication system for this mission. Specifically, customized patch antennas have been realized, and a customized communication protocol has been designed and implemented. The communication subsystem has been validated through an intense testing campaign which included software tests in the laboratory, hardware tests in anechoic chamber, and in flight tests through a balloon experiment.

The article presents an overview of CASTOR mission, a presentation of the trade studies analysis and of the final communication architecture selected, a description of the customized antenna developed, of the customized protocol designed, and a presentation of the results of the tests performed.

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1. Introduction

Cathode Anode Satellite Thruster for Orbital Reposition (CASTOR) is an orbital manoeuvre and transfer micro-

satellite bus developed at MIT Space System Laboratory. The technical objective of the mission is achieving 1 km/s of delta-V over a 1 year mission in Low Earth Orbit (LEO). This will be accomplished using a novel electric propulsion system the Diverging Cusped Field Thruster (DCFT), which enables high efficiency orbital changes of the ESPA-ring class satellite. The DCFT is a customized engine developed at MIT Space Propulsion Laboratory, and it will be the primary payload for the mission. Due to this novel propulsion system, CASTOR is capable of improving rapid access to space capabilities by providing an orbital transfer platform with a very high performance to mass ratio, thus greatly reducing launch costs and allowing for highly efficient orbital manoeuvre. Future missions that aim to achieve rapid orbital transfer capabilities will take great advantage from this technology. Furthermore, CASTOR is highly scalable and modular, allowing it to be adapted to a wide range of scales and applications. This mission is in fact the first of a series of missions. When the capabilities of the thrusters will be demonstrated in orbit, upgraded versions of CASTOR will be launched carrying different scientific experiments.

CASTOR has been developed entirely at MIT during two cycles of a three terms capstone class in which students learn thorough hands-on experience how to design and build a space vehicle. This class is part of the CDIO project which is focused on: '*helping MIT's undergraduate engineering students to develop the skills, tools, and character they will need as future leaders in the world of engineering practice*' [1].

CASTOR has also been part of the sixth University Nanosatellite Program (UNP) Competition [2]. This competition is funded by Air Force Research Laboratory (AFRL), with the goal of increasing the development of students' built space missions.

In order to accomplish CASTOR mission objective, a highly optimized, scalable, light weight, and low cost communication system needs to be developed. These constraints imply the development of trade studies to select the final communication system architecture able to maximize the amount of data transmitted, while guaranteeing reliability, redundancy and limited mass, power consumption, and cost.

Specifically, coverage and feasibility study have been realized to prove the capability of the system of transmitting all the science data required to accomplish the mission. Also, great emphasis has been given to system redundancy. The current design is fully redundant: three antennas and two transceivers provide a completely reliable system while guaranteeing a complete coverage of the spacecraft. A special attention has been given to guarantee a reliable communication system in cases of tumbling, or in case of the strong Doppler shift which is inevitable due to the high delta-V capabilities of the vehicle. To reduce cost, the system has been realized exclusively with custom made or COTS products.

Moreover, in order to accomplish all the mission requirements, different features have been introduced in the design of the communication system for this mission. Specifically, customized patch antennas have been realized, and a customized communication protocol has been designed and implemented.

In terms of space heritage, our system shares some similarities with previous university projects. Specifically, our transceiver (MHX2420) has been already successfully tested in different space missions (Genesat [3], Pharmasat), even at high data rate (MAST [4]). These missions proved the high reliability of this transceiver. Consequently, we selected it as well as other missions currently under development (Oculus [5], Yusend [6], Hermes [7]).

For the antenna's design, different university projects are currently developing customized antenna (helicoidally [8] or patch [9]). Our design is similar in the methodology followed in [9], but it is highly optimized for our mission.

Current protocol development efforts in small satellite mission include the work done by CanX-2 [10] mission with the new NSP (nanosatellite protocol), a customized version of DLC. Differently, our customized protocol is focused on transport level (the first layers are standardized through 802.11g standard), and it provides the efficient feature of a different ARQ mechanism in function of the type of packet sent.

The communication subsystem described in this article has been validated through an intense testing campaign which included software tests in the laboratory, hardware tests in anechoic chamber, and in flight tests through a balloon experiment. The communication system has also been successfully integrated with avionics, power and propulsion, and it is ready to be tested in orbit when the satellite will be launched. The launch date of the satellite has not yet been selected: the team is pursuing different launch opportunities for the next few years.

The article presents an overview of the communication system, and it is organized as follows: first an overview of the mission is given, than the communication system design is presented, hardware components are described, and the software developed is presented. Finally tests' results are discussed.

2. Mission overview

The mission of CASTOR is to characterize the on-orbit performance of the DCFT. This characterization will be accomplished using a broad spectrum of analysis techniques. The primary traits of the DCFT to be characterized are its thrust produced, efficiency, and operational lifetime.

The CASTOR satellite (Fig. 1) has a volume constraint of 50 cm × 50 cm × 60 cm, which greatly limits the maximum power it can generate with solar panels. This limitation leads to constraints in the amount of time the thruster can be operated. To maintain power positive operations and maximize the frequency and duration of the DCFT's operation, the orbit was divided into the following segments: eclipse, charge batteries, and fire thruster. These orbital segments can be seen in Fig. 2. The optimum time for firing the thruster was determined to be approximately 10 min, which equates to a firing angle of 20°. It was chosen to operate the thruster around orbital noon because during this time the most power can be generated by the body fixed solar panels while the spacecraft follows the velocity vector.
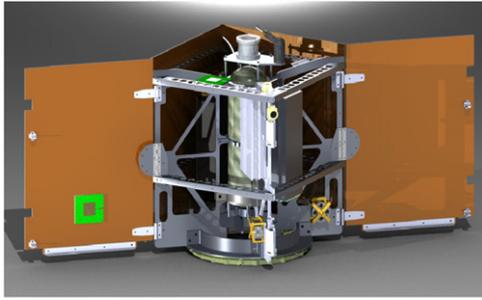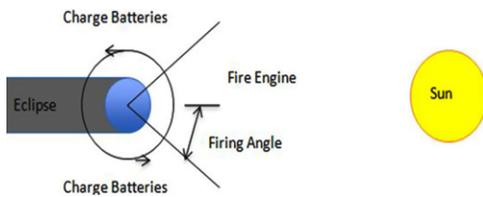
Fig. 1. Castor satellite.

Fig. 2. CASTOR's DCFT operation on-orbit.

The thrust produced by the DCFT is going to be measured by firing the thruster in the ram direction (direction of the velocity vector) and measuring the change in orbital altitude. From this change in the orbital element, the thrust produced can be calculated. To ensure that the thrust measurement is as accurate as possible, this creates several demands upon the satellite bus, and primarily the Attitude Determination and Control System (ADCS), the first of which is to accurately measure the spacecraft's current orbital elements. This is accomplished using Surrey Satellite Technology LTD's SGR-05 GPS receiver, which can determine the spacecrafts position to within 10 m and its velocity to within 0.15 m/s. As a backup to this sensor, the TLE can also be used; however, the frequency of updates and measurement accuracy is significantly reduced. To ensure adequate data is recorded for determining the orbital parameters from the measured GPS data, position and velocity measurements will be collected every 30 s. This accumulates data that must be down linked at a rate of 6.4 bps.

A critical assumption about measuring the change in orbital elements is guaranteeing that the thruster is firing parallel to the velocity vector. The ADCS system minimizes any error in the thrusters' pointing as it is fixed to the spacecraft body. By keeping the error due to inaccurate spacecraft pointing less than errors from other external contributors, the assumption of having the thruster fire in the ram direction can be applied to the thrust measurements. The DCFT produces approximately 4.6 mN of thrust in testing, and the largest anticipated external torque on the spacecraft is less than 1 mN. Thus by keeping the error in thrust measurements from inaccurate pointing below 0.5% it ensures that it is a negligible error compared to other anticipated disturbances. To achieve this level of measurement accuracy requires a pointing accuracy of $< 5°$. An additional order of

magnitude reduction in measurement error can be achieved by increasing the pointing accuracy to $< 1.8°$. These threshold ($< 5°$ of pointing error) and objective ($< 1.8°$ of pointing error) requirements set the requirements for the ADCS sensors and actuators for the CASTOR spacecraft. With this constraint placed on the spacecraft's attitude error, its attitude should remain within the commanded position. For computing the thrust produced, the satellite's attitude will be evaluated to determine any adjustments from thrust produced which is not in the ram direction because the satellite's attitude is not fully aligned with the velocity vector. These satellite attitude measurements will be collected every 30 s, resulting in a data accumulation rate of 12.8 bps.

The next trait being characterized is the DCFT's efficiency, measured in P_{out}/P_{in}. The input power is controlled by the power system and the Xenon flow rate. The power will primarily come directly from the solar panels; however, if additional power is required it can be accessed from the batteries. This electrical energy will then be converted to the DCFTs required anode voltage of 400 V through a DC-to-DC converter. The current is set by the Xenon flow rate. For CASTOR's operations, it was decided to operate the thruster at 210 mA to allow the thrusters to operate for its 10 min duration without requiring power to be drawn from the batteries. Thus the anticipated P_{in} is approximately 84 W. This value is calculated by measuring the voltage and current levels being delivered to the DCFT, recording these values every 10 s results in a data accumulation rate of 6.4 bps.

The output power is calculated from the thrust produced and the change in the spacecraft's velocity. The calculation of the thrust produced was discussed previously. The spacecraft's change in velocity can be calculated from the GPS data collected to determine the thrust. Thus no additional data must be collected to determine P_{out}. The anticipated efficiency of the thrusters is approximately 43%.

The final trait of the DCFT being analyzed is its operational lifetime. As the CASTOR bus cannot guarantee continual operation until the DCFT fails, this trait will primarily be analyzed by collecting color images of the thruster in operation. The color of the thrusters' plume indicates the level of ionization occurring, which are indicative of the thrusters' remaining operational life. Additionally, degradation of the thruster body can be monitored in the images. These images will be collected as 640×480 pixel 24-bit color JPEG encoded pictures. Each time the thrusters are operated, two images will be collected, for a data accumulation rate of approximately 274 bps. These image files constitute the majority of the spacecraft's telemetry data that must be down linked (as it constitutes $> 80\%$ of the total telemetry data).

Thus the mission of CASTOR is to characterize the on-orbit operating characteristics of the DCFT by measuring its thrust produced, efficiency, and lifetime. These measurement requirements created several requirements for the satellite bus, to include the ADCS pointing accuracy, the power system generation capability, and the communication system's capability to effectively downlink the data collected.

3. Communication system overview

Designing the CASTOR communication system implies facing different challenges given by several constraints. Specifically, the considerations and the requirements taken into account in the design of the system are the following:

1. *Feasibility*: the communication subsystem has to provide reliable communication link to download more than 221 Mbit of science data and more than 5.6 Mbit of telemetry data per day.
2. *Mission velocity*: the communication system needs to be able to support a Doppler shift of approximately 8 kHz.
3. *Cost*: the communication system has to be realized with COTS products or with products manufactured in house in order to minimize costs.
4. *Mass and power*: since the total mass of the satellite has to be less than 50 kg, the mass allocated to the communication system is not more than 2 kg. Also the power consumption needs to be less than 10 W, since the great proportion of power is required to activate the DCFT.
5. *Tumbling*: the system needs to provide coverage in the case of satellite tumbling.
6. *Ground station*: in order to reduce the operational cost for the mission, a ground station owned by MIT, or available at no additional charges is necessary.
7. *Redundancy*: in order to ensure communication with the satellite, the system has to be fully redundant.
8. *Reliability and security*: commands messages need to be transmitted reliably and correctly to the satellite.
9. *Material*: all the material used should be compliant with thermal regulations.

All these considerations required a complex analysis to develop the best possible design able to accomplish mission requirements while still respecting all the constraints. Specifically, feasibility drove link budget and coverage analysis (more details in the following sections), Doppler shift drove the requirement on the data rate, cost and material issues determined the development of customized patch antennas (more details in Section 4). Constrained in mass and power drove the amount and type of antenna selected, while the needs of providing communication while tumbling affected the antennas' placement on the spacecraft. The necessity of limiting ground station's cost caused the selection of HETE ground station and drove the selection of the S-Band as central frequency. Redundancy affected the whole architecture, while reliability in messages transmissions determined the development of a customized communication protocol.

The following sections of the article are dedicated to each of the previous issues, as well as to the presentation of the hardware selected and of the software features implemented.

3.1. Data rate and Doppler analysis

One of the biggest concerns in designing CASTOR communication system given by the Doppler shift. Since the satellite is equipped with an engine able to reach 1 km/s of Δv, the correspondent Doppler shift at 2.4 GHz is approximately 8 kHz. Since the transceiver selected for the mission is a COTS product (more details in the hardware section) designed for terrestrial application which does not include a Doppler tracking and correction, some analysis were required to solve this issue. Fortunately, a detailed examination of the transceiver [11] selected revealed that the bandwidth of the modem is large enough to track the shifted signal if the data rate is greater or equal to 115.2 kbps. For this reason the data rate selected for the mission has been fixed to this value.

3.2. Ground system

CASTOR will communicate to Earth through HETE ground station system. HETE [12] is a network of ground station owned by MIT Kavli Institute, and developed for the HETE project in the 1990s. The network includes three stations located in Cayenne (French Guinea), Singapore and Kwajalein (Marshall Islands). Each station is equipped with a 2.4 m dish (which will soon be upgraded to a 3 m dish), and it can provide a data rate up to 250 kbps in the S-Band. An image of the Kwajalein station is shown in Fig. 3.

Data from each of the ground station are transmitted to MIT Control Centre (MCC) over TCP/IP connection. More information on MCC is discussed in the software section of this article. In terms of design, the selection of HETE as the primary ground station drove the requirement on the central frequency to be in the S-Band.

3.3. Link analysis

Given the constraint previously discussed, a link analysis was developed. The link analysis [13] for CASTOR is illustrated in Table 1. In the table the downlink (from the satellite to the ground station) is presented, and the best and worst cases (determined by the distance) are discussed.

3.4. Feasibility analysis

The feasibility analysis performed is similar to the one performed in [14]. It is developed through custom made software that integrates orbit and link analysis to identify

Fig. 3. Kwajalein ground station.

Table 1
Link analysis.

Element of link analysis (downlink)	Value
R (data rate in bps)	115,200.00
EIRP (dBW)	6.00
Rx antenna gain (dB)	35.30
Bandwidth (Hz)	83,500,000
Eb/N0 required (dB)	12.80
f (central frequency in MHz)	2442.00
θ (earth centric angle at maximum distance in rad)	0.45
Circular orbit altitude (km)	700.00
Additional losses (atmospheric, ionospheric, gas losses, pointing, demodulation, splitter loss, line loss)	−8.91
Max. distance (km)	3067.48
Min. distance at Zenith (km)	700.00
Max. space loss (dB)	−169.94
Min. space loss (dB)	−157.11
System noise temp (dBK)	−27.99
Eb/No-max. (dB)	16.62
Eb/No-min. (dB)	29.45
System margin (max. distance, (dB))	3.82
System margin (min. distance, (dB))	16.65

Fig. 4. Data download analysis.

whether the system is able to download all the required data in the communication windows available. The analysis is performed through the following steps:

1. The orbit simulator is activated and the satellite is put in a LEO orbit with 700 km of altitude, 0° of elevation and 5° of inclination.
2. The simulator computes the total coverage between the satellite and the ground stations and it represents the coverage as a binary vector (zero for non-coverage, one for coverage).
3. The data accretion on the satellite is simulated as a linear function with an increase rate of

$$R_{increase} = \frac{\text{Data}_{science} + \text{Data}_{telemetry}}{T_{collection}} = 2.6 \text{ kbps} \quad (1)$$

4. For any instant of zero coverage the system accumulates data on board, while for any instant of coverage the satellite is assumed to transmit and discharge its data at the data rate of 115,200 kbps.

The result of this analysis is represented by the discharge plot which shows the amount of data cumulated on board. The objective of this analysis is to check that the amount of data cumulated goes periodically to zero: this means that the satellite has enough transmission time and data rate to be able to transmit all the data cumulated. The results of this analysis are shown in Fig. 4.

It is possible to notice that data are cumulated periodically in the interval of time in which the satellite is not in coverage. However, cumulated data (up to not more than 5 Mbit per window) tend to be downloaded periodically with some margin. These results show that the data rate selected is sufficient to download all the data, proving the feasibility of the communication system.
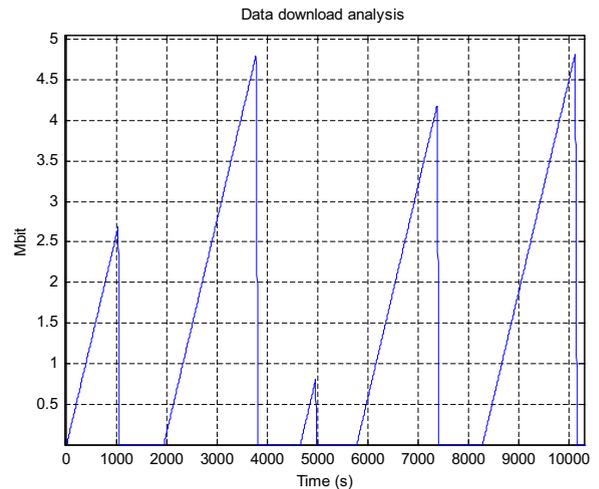
Table 2
Summary of CASTOR communication components.

Component	Units	Mass per unit (g)	Power consumed per unit (W)	Volume per unit (mm³)
Custom patch antenna	3	59.5	0	21,911
MHX2420 transceiver	2	55	4.5	84,600
Power splitter	1	170	0	65,500
Total	6	458.5	9	172,100

More details on the hardware and the software features of the system are presented in the following sections.

4. Communication system hardware

The CASTOR communication system consists of different components selected to meet design and mission requirements.

Key features of this design are the redundancy, and the complete coverage. Multiple antennas are located in different parts of the spacecraft in order to obtain an omni directional coverage while still having 6 dB gain for any antenna. The system is fully redundant, since it can tolerate up to two antennas and one transceiver failure. In case of failures the coverage is reduced, but the system maintains its functionality.

Table 2 shows an overview of the components used on CASTOR. It is possible to notice that CASTOR uses a passive splitter instead of an active switch. The choice has been driven by simplicity: a switch would have added a power and command line to the system. The splitter causes 3 dB loss, but since the link analysis shows that the system can afford that loss the team has opted for the splitter.
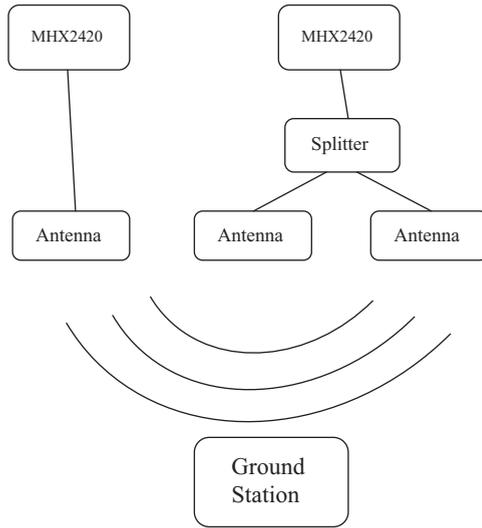
Fig. 5. Communication system overview.

Table 3
Antenna design requirements.

Parameter	Requirement
Gain	5–6 dB
Central frequency	2.442 GHz $\pm$ 0.01 GHz
Half-power beamwidth	$60° \pm 10°$
Impedance	$50\,\Omega \pm 8\,\Omega$

Table 4
RT duroid 5800 properties.

Property	Symbol	Value
Dielectric constant	ε_r	2.2
Dielectric thickness	h	1057×10^{-3} m

The satellite is equipped with three custom patch antennas and two modems for redundancy. One antenna is located on the backside of one of CASTOR's solar panels. A second antenna is located at the top of the satellite, opposite to the thruster exit, and the third antenna is located on the bottom near the thruster exit. The antenna on the solar panel is considered the primary antenna, and it is connected to one of the MHX2420 transceivers. The other two antennas are secondary antennas, and they will be used during tumbling or as needed by the mission requirements. The backup antennas are connected to the second transceiver via a power splitter.

The communication system designed in this way achieves three objectives: coverage, redundancy and simplicity. The multiple antennas guarantees coverage for the satellite independently from the pointing ability of the control system: in this way the satellite can be reached even in tumbling conditions. At the same time, the system is fully redundant against up to two antennas failures and one transceiver failure. Finally, the selected architecture is simple and minimizes the power consumption since the only two active components are the two transceivers.

Fig. 5 is a visual overview of the communication system.

The following sections describe in more detail the antenna design and the other components.

4.1. Antenna design

CASTOR is equipped with three custom made patch antennas but the original design consisted of Commercial off the Shelf (COTS) patch antennas. The COTS antennas were dropped from the design because there was concern that they would not be able to withstand the vibration loads ($=20$ g) on the satellite during launch. The purchase of space-qualified patch antennas was also dropped due to their very high costs.

Hence, the design choice was to design specific customized antenna. In this way, CASTOR has been equipped

with antennas specifically optimized for the mission's necessity and at the same time affordable with the mission total budget.

The design requirements for the antennas are summarized in Table 3

The first step taken in the design process is to perform initial hands on calculations using the equations governing microstrip pitch antennas. These calculations are used to validate the numerical model developed in software. Also, they are used as initial conditions for the final optimization of the design. An overview of material properties is given in Table 4.

Using the constants shown in Table 4, we calculate the width of the radiating copper plate to be [15]

$$w = \frac{c}{2f_c\sqrt{((\varepsilon_r+1)/2)}} = 48.56 \text{ mm} \qquad (2)$$

The effective length and the effective dielectric constants result [15]

$$L_{eff} = \frac{c}{2f_c\sqrt{\varepsilon_{eff}}} = 41.78 \text{ mm} \qquad (3)$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{w}\right)^{-1/2} = 2.137 \qquad (4)$$

We calculate the length extension to take into account the fringing effects [15]:

$$\Delta l = \frac{0.412h(\varepsilon_{eff}+0.3)((w/h)+0.264)}{(\varepsilon_{eff}-0.258)((w/h)+0.8)} = 0.51 \qquad (5)$$

Finally, we calculate the length to be [15]

$$L = L_{eff} - 2\Delta l = 39.75 \text{ mm} \qquad (6)$$

The second step in the design process involves numerical analysis through electromagnetic wave solver software. The initial design is drawn in the program and then by inputting the desired central frequency and dielectric constant into the program, a ground plane, feed line and quarter wave transformer are added to the design that gives the antenna the desired parameters.

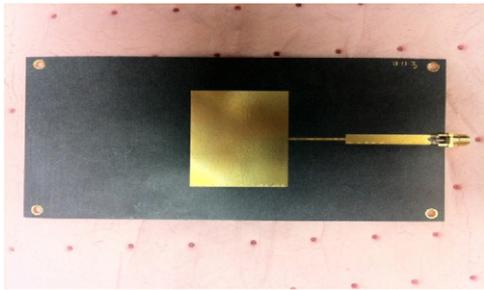The third step involves fine tuning the antenna design using an optimization and simulation tools in order to

Fig. 6. Custom made patch antenna.

Fig. 7. Protocol Stack.

meet design requirements. Fig. 6 shows the final antenna. Tests' results for the antenna are discussed in Section 4.

4.2. Modem and splitter

CASTOR is equipped with two MicroHard MHX2420 [11] modems. They operate within the 2.40–2.84 GHz range and use Frequency Hopping Spread Spectrum (FHSS). They output a maximum of 1 W for a maximum of 4.5 W power consumption. The modems are set up to a data rate of 115.2 kbps; refer to Section 3.1 for a detailed explanation on data rate selection. From a network point of view, the two satellite modems are considered slaves while the ground station modem acts as a master. The modems are set up in a Time Division Multiple Access (TDMA) network. As stated in Section 1, the MHX2420 are the selected modems due to their space heritage.

CASTOR is equipped with a power splitter that connects the two secondary patch antennas to the second modem. It functions within the 2.00–4.20 GHz range and it is a 0° phase change splitter with an impedance of 50 Ω. It attenuates input signals by 3 dB. The power splitter is included in the design because of the requirement of having the two secondary antennas transmitting and receiving simultaneously if CASTOR were to go into a tumbling mode.

5. Communication system protocol

The CASTOR software protocol is responsible for receiving and interpreting a packet sent from the ground station to the satellite. It must correctly identify packet type, and send relevant data to the avionics board microprocessors for command execution. It must be reliable and robust, accounting for incorrect packets, and handling any errors autonomously. The CASTOR software protocol follows the standard seven layer OSI model for communication systems. Key layers for the communication system include the physical, data link, routing, and transport layers.

The physical and data link layers are already implemented in the MHX2420 modems and follow the 802.11g standard. The routing layer is not implemented given the point to point nature of the network. Hence, the bulk of the work for the software protocol development lies in the implementation of a reliable and robust transport
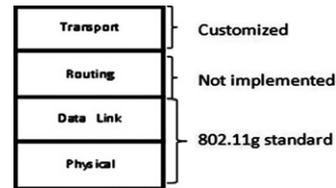
layer customized for our necessities. Fig. 7 summarizes the protocol stack.

The following sections describe the different protocol layers in details.

5.1. Standardized layers: physical layer and data link layer

The physical and data link layer of the CASTOR communication protocol are not implemented by the MIT satellite team. These layers are implemented directly on the modems. MHX2420 [11] uses the 802.11g standard at a central frequency of 2.442 GHz.

The signal is modulated in the physical layer using Differential Binary Phase Shift Keying (DBPSK) modulation. Data link layer features include FEC Coding (Hamming/Reed Solomon), error detection and packet retransmission (up to a maximum amount of retransmissions which is selected by the user), and framing. The maximum packet size (255 bytes) is defined in this layer.

For data encryption, the modems come with an added feature that allows data to be encrypted at the data link layer. The type of encryption supported by MHX2420 is 128-AES.

Since CASTOR is only communicating with the ground station via a point to point link, the routing layer does not need to be implemented.

5.2. Customized layer: transport layer

The transport layer of the communication protocol is completely designed and implemented by the MIT satellite team. This layer is responsible for packet definition, communication reliability, end to end error checking, retransmission, and flow control.

The ground station communicates with CASTOR whenever CASTOR is within range of communication. Every communication session is initiated by the ground station which sends a set up packet. At that point, if the packet is correctly received, CASTOR transmits an acknowledgments packet (ACK packet), and the communication session is initiated. CASTOR requires a set of initial set up packets in order to decide which of the two modems on board will be used in a specific communication session. The selection depends on which antenna is in view of the ground station.

A communication session between CASTOR and the ground station can consist of a sequence of commands and/or down linked files. Down linked files are either telemetry data files or images. All files are stored onboard CASTOR on an SD card. At the end of communication, the ground station sends CASTOR an end packet and with an

Table 5
CASTOR packet header.

Header field	Bits	Description
Start flag	8	Sequence used for framing purposes
Origin	1	( )→ castor 1→ ground station
Ack or nack identifier	1	0→ ack 1→ nack
Requires ack as an answer	1	0→ no 1→ yes
Type	5	See packet type description in
Length	8	Integer number which defines the amount of bytes contained in the packet
CRC	8	See description in Section 5.2
Time sent	32	Date and time in which the packet has been sent
Packet ID	32	Sequential number of the packet

Table 6
Packet types.

Packet type	Description
None	Generic packet
Empty	Generic packet
Set up	Initiating communication
Normal command	Various commands, able to be scheduled or executed immediately
Critical command	Time critical command to be executed immediately
Telemetry backlog	Used for down linking files that contain telemetry logs
Telemetry current	Sending current telemetry readings
Image	Used for sending images to the ground station
Debug text	Used for debugging communication protocol software

acknowledgment (ACK) reception, terminating communication.

For the transport layer packet, a specific packet structure has been defined. The 12 byte header of the packet contains standard information and it is defined in Tables 5 and 6. The packet type field in the header corresponds to one of nine different enumerations. In addition, command packets can have 45 different commands ranging from executing satellite manoeuvres, firing satellite thruster, requesting telemetry data, reading the SD card, etc.

The error detection in the customized transport protocol is performed using a Cyclic Redundancy Check (CRC). It is 8 bits long and generated using a polynomial. To generate the CRC, the data stream is shifted 8 bits to the left, creating eight zeros at the end of the data stream. The data is then divided by the polynomial. At the end, the remainder, which will be 8 bits long, is the CRC.

The received data must be verified by using the CRC. On the receiving end the communication protocol will receive a packet, generate the CRC in the same manner, and check to see that the CRC that was just generated is equal to zero. If so, then the data packet does not contain errors. If not, then the data is corrupted and the packet must be retransmitted.

The CASTOR Satellite communication protocol must be able to detect faulty packets and automatically request that new packets be sent. However, since there are

different types of packets and different actions that CASTOR takes to carry out specific commands, different automatic repeat request (ARQ) protocols must be used. A Stop and Wait ARQ is used when sending normal command packets and a slight variant of a Selective Repeat ARQ is used for down linked telemetry and image files.

In a Stop and Wait ARQ for commands, the ground station sends a normal command to the satellite and waits to receive an ACK packet back from the satellite before issuing another command. In the event that an ACK packet is not received, the ground station shall automatically resend the command packet after a timeout window, S, which must be equal to or greater than the total transit time of the packet and ACK plus any time for processing. A Stop and Wait ARQ is the best choice for normal commands because the ground station must issue commands one at a time (each command is also only one packet) to CASTOR with confirmation that CASTOR has received that command.

Instead, a version of a Selective Repeat ARQ is more efficient when CASTOR is sending multiple packets to the ground station. In CASTOR's Selective Repeat, the transmitter (the satellite) sends all packets in a row. As part of the packet, the receiver (the ground station) knows which packet is being sent, and how many total packets the satellite is going to transmit. The ground station then marks the packets that have not been received. After all packets have been sent, the ground station sends a final packet to the satellite which contains the list of the packets (indicated by the packet numbers) that have been lost. The satellite receives this automatic request for specific packets and resends those packets to the ground station. This process continues iteratively until the ground station sends an empty packet to the satellite indicating all packets have been correctly received. This variation of Selective and Repeat is particularly suitable for large files downloading because those files are fragmented and sent by the satellite in hundreds of packets. It is consistently more time efficient to implement this selective repeat and automatically retransmit only those packets that have been lost, instead of applying the Stop and Wait ARQ methodology to the overall communication session.

Hence, the use of different ARQ systems guarantees the highest level of security for commands reception, but in the same time improves the efficiency of the transmissions, which would have been very slow using Stop and Wait for any packet. A simple comparison in terms of efficiency can be done between a traditional Stop and Wait protocol and our Stop and Wait/Selective Repeat protocol variation.

It is known [16] that the efficiency of a Stop and Wait ARQ protocol can be computed as

$$E_{stop\ and\ wait} = \frac{T_{packet}}{T_{packet} + 2T_{prop} + 2T_{process} + T_{ack}} \quad (7)$$

where T_{packet} is the time to transmit a single packet which in the worst case scenario, for a maximum packet length of 255 bytes, results

$$T_{packet} = \frac{L_{packet}}{R} = \frac{255\ \text{bytes}}{115200\ \text{bit}/s} = 17.7\ \text{ms} \quad (8)$$

where T_{ack} is the time to transmit an acknowledgment packet which depends on the actual length of the packet. In the worst case scenario, it is exactly equal to T_{packet}. $T_{process}$ is the time required by the processor on the satellite and on the ground station to process the packets. This time is in the order of micro-seconds: hence, it can be considered negligible for this calculation. T_{prop} is the propagation delay, which for the maximum possible distance results

$$T_{prop} = \frac{d}{c} = \frac{3067 \text{ km}}{3 \times 10^8} = 10.2 \text{ ms} \qquad (9)$$

Hence, the efficiency for the STOP and Wait ARQ is

$$E_{stop \ and \ wait} = \frac{17.7}{2 \cdot 17.7 + 2 \cdot 10.2} = 0.317 = 31.7\% \qquad (10)$$

Our protocol is a combination of Stop and Wait for command packets, and Selective Repeat for data (telemetry and images) packets. Hence, if we define as w_c and w_d the weights of data and commands (which indicate percentages of commands packet transmitted and percentages of data packets transmitted), the efficiency for our protocol can be computed as

$$E_{combined} = w_c E_{stop \ and \ wait} + w_d E_{selective\_repeat} \qquad (11)$$

The efficiency of a Selective and Repeat protocol [16] depends on the error probability for the channel, which in our case is 10^{-5}. Hence

$$E_{selective\_repeat} = \frac{1}{1 + p_{error}} \approx 1 \qquad (12)$$

Substituting $E_{stop \ and \ wait}$ and $E_{selective\_repeat}$ in Eq. (11), and estimating $w_c = 0.1$, $w_d = 0.9$, we obtain

$$E_{combined} = 0.1 \times 0.31 + 0.9 \times 1 = 0.931 = 93.1\% \qquad (13)$$

It is possible to verify that the estimated $E_{conbuned}$ (93.1%) is much greater than $E_{stop \ and \ wait}$ (31%). Also, the proportions of data with respect to commands is expected to be much greater than 0.9; hence the real efficiency for our protocol is expected to be even greater.

The following section is dedicated to the hardware and software tests conducted on the communication system.

6. Testing and results

This section summarizes the tests performed on the communication system for both hardware and software.

6.1. Hardware tests

Performance tests were done to the antenna, modems and power splitter in order to ensure that they were working according to CASTOR's design requirements.

Specifically, the antenna was tested to obtain the following:

- Central frequency around 2.442 GHz.
- Peak gain of 6 dB.
- Polar diagrams hemispherical for both planes.
- Half-power beam width greater than 60°.
- Impedance of 50 Ω.
- Bandwidth of at least 50 MHz.

The modems were tested to verify the following:

- Successful transmission/receiving of data packets.
- Functionality of TDMA network.
- None or minimal packet collision and packet loss when transmitting/receiving simultaneously from both slave modems.

The power splitter was tested to obtain the following:

- S11 parameter as a measure of the strength of signal reflections (smaller than -20 dB).
- S12 parameter to verify that signal attenuation across the splitter is not more than -3 dB.

6.1.1. Antenna tests

The antenna's performance was fully tested in the anechoic chamber. We found that the max gain was 6.03 dB (Figs. 9 and 10) at a central frequency of 2.45 GHz, with a bandwidth of around 60 MHz (Fig. 8). The obtained polar diagrams showed the antenna had a hemispherical radiation pattern with a half power beam
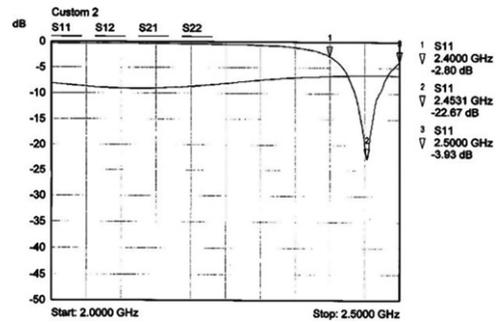

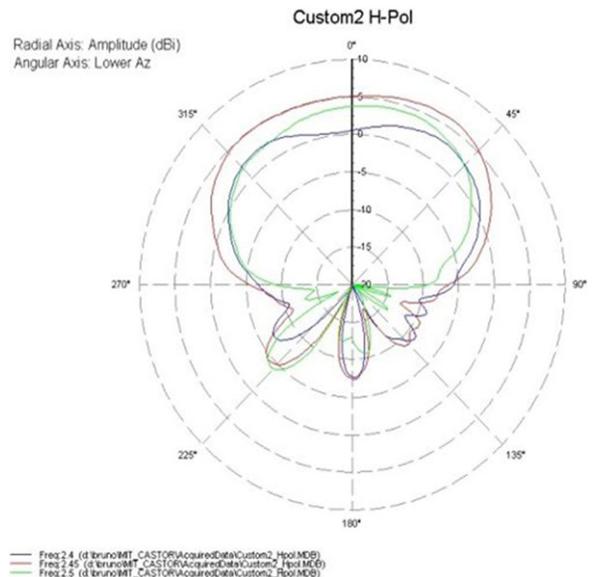Fig. 8. Frequency spectrum for the antenna.
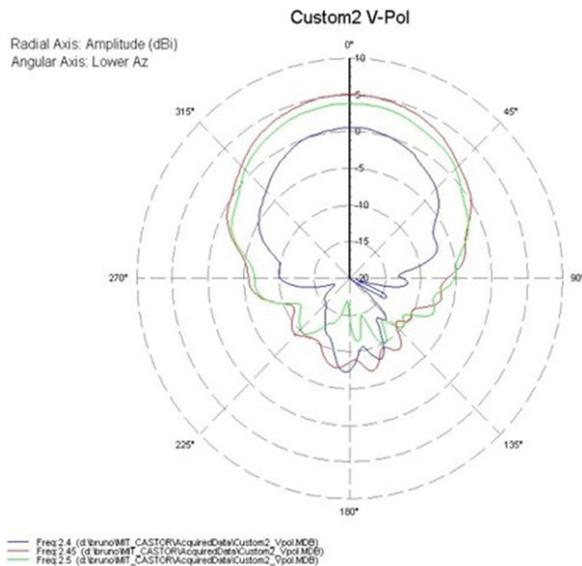

Fig. 9. Antenna polar diagram (horizontal plane).

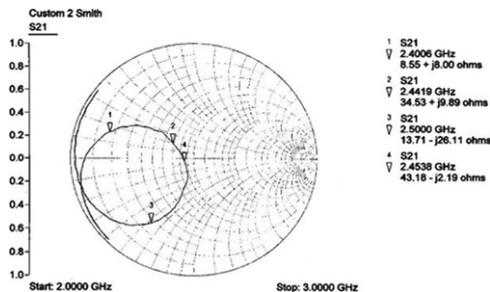**Fig. 10.** Antenna polar diagram (vertical plane).

Fig. 11. Smith chart for the antenna impedance.

width of 68° in the horizontal plane (Fig. 9) and 60° in the vertical plane (Fig. 10). Thus, the results of the parameters fell within our required design range.

We observed a slight mismatch in the impedance of the antenna which was found to be 43.18 Ω (Fig. 11). The team is currently trying to improve the design to fix the mismatch. However, the loss caused by the mismatch still allows the antenna to meet the desired requirements.

6.1.2. Modem and splitter tests

The first modem test involved transmitting and receiving sequences of bits from each individual slave to the master modem. We found that the bits were successfully transmitted and received from each slave to the master. In addition when one slave sent stream of bits, the other one would not receive that stream and vice versa. We also found that when the master modem transmitted, both slaves would receive data. These results demonstrate that the modems were functioning correctly in a point to multi point TDMA network.

In order to verify minimal packet collision and loss between the modems we sent 1000–8000 byte files of information from each slave to the master simultaneously through multiple tests. We found that very few bytes were lost within this, but the amount of bytes lost slightly
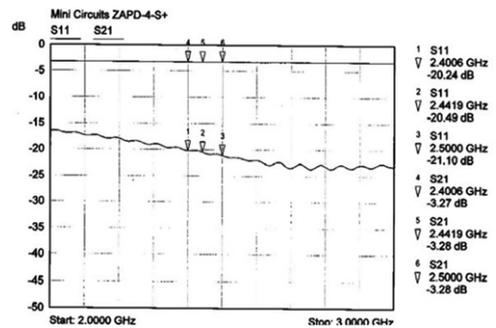

Fig. 12. Splitter test results.

increased as the size of the files increased up to 8000 bytes. Transmissions larger than 8000 bytes saw significant byte loss and we concluded that the reason was due to the 8000 byte buffer limit on the RS232 interface buffer.

The splitter was tested by connecting it to a Vector Network Analyzer in order to obtain the S11 of the port connected to the modem, and the S12 parameters of the ports connected to the antennas. We found (Fig. 12) that the S11 parameter was −20.49 db and therefore the splitter has very low signal reflection. The S12 parameters were found (Fig. 12) to be −3.2 dB which confirms the splitter is working properly and is within our design requirements.

6.2. Software tests

Communication protocol tests were designed to verify that requirements on software were met. More specifically, tests verified the ability to send and receive packets to CASTOR as well as ensuring packets were interpreted correctly and errors were dealt properly.

6.2.1. Flatsat test

The purpose of the Flatsat tests is to test the specific communication software in an isolated environment. A simulated HETE ground station (created with an antenna, a modem and a computer), was connected to the MIT Control Centre computer through TCP/IP. Then, packets would be packed and sent to the satellite for interpretation.

Testing procedures included the following:

- Sending normal command packets to the satellite including reading current telemetry values, commanding xenon flow to fire thrusters, and downloading telemetry and image files.
- Verifying that the satellite has acknowledged receipt of these command packets.
- Verifying that the received data packets contained correct values.

In addition, the special ARQ protocols were tested separately by forcing specific packets to fail transmission. Both the Stop and Wait ARQ for normal command

packets, and the Selective Repeat ARQ variation were tested and verified in this manner.

Through testing and verification, the communication software protocol successfully passed all tests and was concluded to be functioning properly.

6.2.2. Shot test

Through a University Nanosatellite Program (UNP) sponsored test, the CASTOR avionics and communication system was tested and verified in a weather balloon. The main goals of this weather balloon test were to

- demonstrate proper communication setup.
- demonstrate reliable communication in a continually running test, and
- demonstrate capability to store test data in flight for later verification.

Proper setup was verified as the satellite avionics and the communication system was able to start from a hard shutdown, and initialize communication to the ground station successfully. Unfortunately, the avionics board software locked up due to a mishandled thread error, and communication was lost with the satellite minutes after launch. However, after further verification after testing was complete, and some data were restored in the satellite SD card.

6.2.3. Chamber test

A vacuum chamber test was performed to verify proper integration between the avionics and communications subsystems in a completely isolated environment. The test was required to be performed in a vacuum chamber in the Space Propulsion Laboratory at MIT, before the tests with the real thruster. Upon placing the satellite equipment and ground station antenna in the chamber, the door was closed and command packets were sent to the satellite in the same manner as the previous Flatsat test.

The test was successfully completed as communication to the ground station was properly established and command packets were sent and interpreted correctly on the satellite.

7. Conclusion

This paper presents a description of the communication system designed for CASTOR satellite.

In order to accomplish CASTOR mission objective, an optimized, scalable, light weight, and low cost Communication System needed to be developed. The article described the principal tradeoff experienced and the correspondent design choices. The features of the system (custom designed antenna and custom reliable protocol) are presented. Results from different tests seem to confirm the capability of the system to provide the communication service required. In the last months, the Communication System has been completely integrated and tested with the rest of the vehicle. The satellite is in the last phases of integration and development.

Unfortunately, with the loss of UNP competition the satellite will not be launched in the next year. However, new launches opportunities are currently under consideration by CASTOR team.

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