ConSat-0
Earth-Observing Satellite
Mission Design and Simulation

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Abstract— **The ConSat-0 project involves the design, analysis, and simulation of an Earth-observing satellite system. This project delivers a non-spaceworthy implementation of an Earth-observing CubeSat. In the project many of the main aspects of designing a satellite are covered, including embedded system design and programming, imaging, a geomagnetic Attitude Control System (ACS), and solar energy conversion. A satellite-ground station pair is proposed whereby measurements of a subset of Earth's ice features (such as polar ice and glaciers) can be made at regular seasonal intervals over an extended period of time. The motivation is to provide climatologists with raw data upon which predictions of future global temperature trends can be made. This report discusses the implementations of ECEF, WGS-84, ISO 6709:1983, IEEE 802.15.4c and IEEE 754-2008 industrial standards in the project.**

Keywords— **CubeSat, Earth-observing satellite, Simulation, ConSat-0, ECEF, WGS-84, IEEE 802.15.4c, IEEE 754-2008**

I. INTRODUCTION

Humankind's presence on Earth has been largely benign on the planetary scale for millennia. Recently and through his industry and ingenuity, Man has inadvertently begun to manipulate the pre-existing natural processes which govern life as it is known today. Since the beginning of the Industrial Revolution in the 18th century, an increase in greenhouse gas emissions has altered the Earth's remarkable ability to absorb precisely the quantity of energy from the Sun necessary to sustain life in the biosphere, and reflect the excess back into space, a process known as the greenhouse effect. The quantity of greenhouse gases in the atmosphere has increased by 30% since the beginning of the Industrial Revolution [1]. This translates to an increase in the average global temperature; a phenomenon known as global warming.

In this project, an Earth-observing CubeSat was built with the base station and a polar image collection mission was simulated. The scope of the project involved designing and building a complete satellite system. Given that some scientific satellite projects are implemented over several years at costs in the millions, the size and complexity of the satellite, named ConSat-0, was set accordingly with a launch-prohibitive budget. A computer was used to interface with the satellite over wireless communication channels. The satellite carried an imaging payload under the auspice of being an environmental Earth-observation satellite. Its orbit carried it over the poles of the Earth, where it photographed ice coverage, and then over the ground station, the images were downloaded. We followed a specification which has been designed specifically to facilitate the deployment of small satellites, namely the CubeSat Standard.

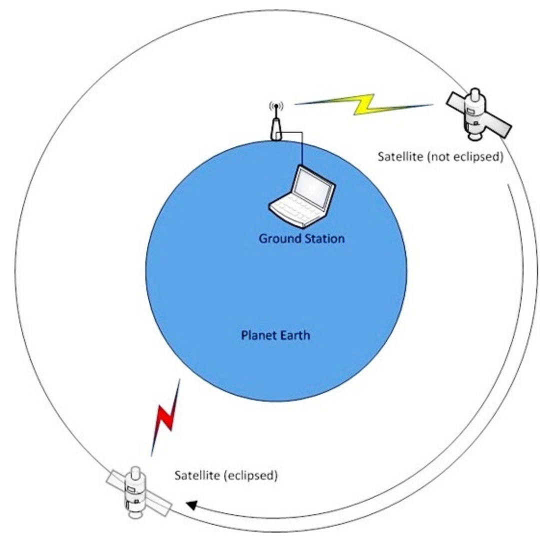

Fig. 1 Communication during the Mission

This report will discuss implementations of ECEF, WGS-84, ISO 6709:1983, IEEE 802.15.4c and IEEE 754-2008 standards in this project.

II. SYSTEM OVERVIEW

ConSat-0 project follows to the CubeSat specifications closely. We have defined the boundaries between an actual and a simulated satellite system. For its Attitude Determination System (ADS) and Attitude Control System (ACS), we have chosen Geomagnetic and Electromagnetic systems respectively by taking into account their pointing accuracy, power consumption, weight and cost. We have decided to use a color CMOS camera that is low cost with digital 8-bit outputs and low power consumption. For the wireless communication system, after comparing with both Bluetooth and ZigBee, we have decided to use RF transmitter/

receiver because it is the most realistic and suitable for a CubeSat.

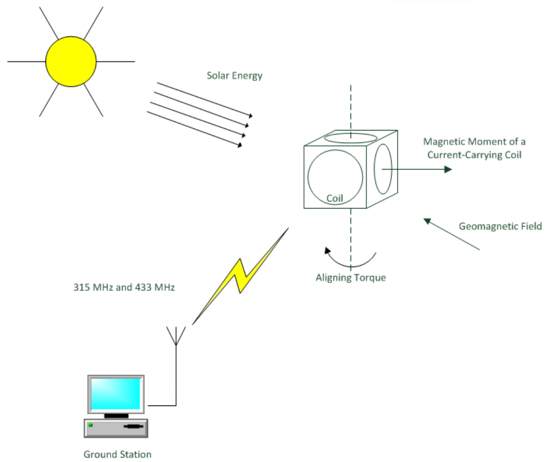

Fig. 2 Satellite System Overview

For the mechanical component, we have decided to use an aluminum-based square design to once again follow the CubeSat standards. The power system is consisted of solar panels, batteries, 2 voltage buses (3.3 V and 5 V) and charging circuit. We are using 18 Polycrystalline Blue Solar Cells. Even though initially we considered using two MCUs, we decided to use one microcontroller, Atmega644, that has enough ports to be used in the satellite. We are using serial EEPROM for supplemental data storage.

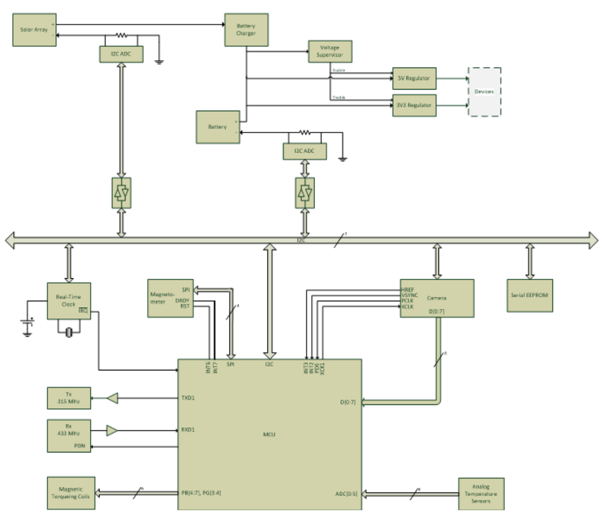

Fig. 3 System Block Diagram

We programmed a real time system without OS for ConSat-0 Software, which has a modular design with five modes that are System Check Mode, Picture Mode, Communication Mode, Sleep Mode and Stabilization Mode. Meanwhile a Ground Station Application was developed in MATLAB which is used for satellite tracking and data exchange. It was also used to visualize numeric telemetry data because of its native plotting functionality. We used rechargeable polymer lithium-ion batteries for the satellite system.

III. Implementation of Standards

This section gives information about the systems that the standards were implemented and how the implementations were made.

A. Attitude and Orbit Determination and Control System

The attitude control system consists of a sensor, actuators, and a controller. The sensor, a magnetometer, provides readings of the external magnetic field due to the Earth in three orthonormal directions. It is positioned in the satellite so that it aligns with the three principle directions of the satellite reference frame. The actuator is three electromagnetic coils of equal size and number of turns orthogonally positioned on the outside of the satellite. The idea is to manipulate the current flowing through each coil to induce an aligning toque with the external magnetic field (the Earth's geomagnetic field) until the desired attitude is achieved. The control loop is given below:

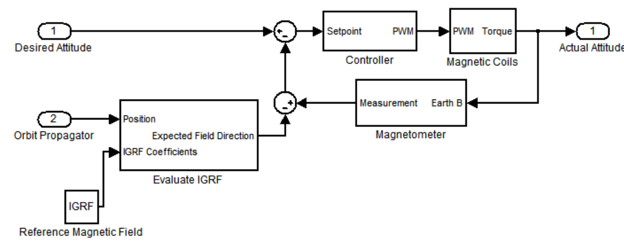

Fig. 4 ACS Control Loop

The control system has two inputs: the desired attitude and the current satellite position. The desired orientation is expressed relative to the Earth. The controller determines the intensity and orientation of the magnetic moment generated by the coils. The magnetic moment produces an aligning torque with the external field. The Earth's magnetic field changes as the satellite's position changes, requiring the controller to include a reference magnetic field against which to compare the magnetometer readings. This is provided by the International Geomagnetic Reference Field (IGRF). The National Geophysical Data Center (NGDC), a division of the National Oceanic and Atmospheric Administration (NOAA) provides up-to-date data and computer code to evaluate the Earth magnetic field at a given location [2].

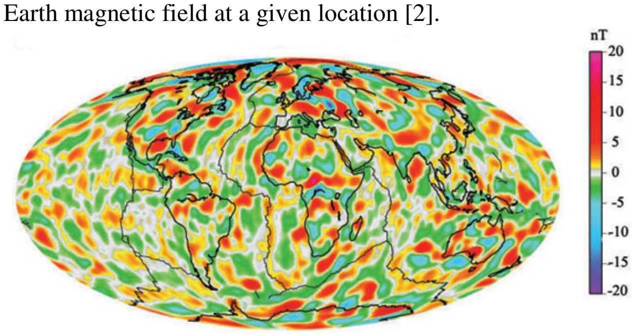

Fig. 5 Geomagnetic Field Anomalies [3]

The use of the IGRF provides a 15 arcminute resolution, which at an orbital altitude of 750 km corresponds to less than 120 km. The satellite has no direct (hardware) method to determine its position in space. An alternative method providing sufficient resolution is used, again based on freely available data. The North American Aerospace Defense Command (NORAD) tracks all satellites in orbit around the Earth. The orbits are characterized by a set of Two-Line

Elements (TLE) which are based on the six Keplerian Elements, (named after the German astronomer Johannes Kepler, 1571-1630) which define an elliptical frame of reference in which the satellite propagates. These elements are Eccentricity (describes the shape of the ellipse), Semimajor Axis (describes the size of the orbit), Inclination (describes the orientation of the orbit), Longitude of the Ascending Node (describes the orientation of the orbit), Argument of the Periapsis (describes the orientation of the orbit) and Mean Anomaly (describes the position of the satellite at the reference epoch).

The TLE add more data, namely the time derivative of the mean motion (i.e. the satellite's velocity) and a drag coefficient. The TLE for Cryosat-2 are available online from http://celestrak.com/:

```
CRYOSAT 2
1 36508U 10013A   11085.87966594  .00000003  00000-0  00000+0 0  3004
2 36508  92.0282  12.0850 0011208 148.4933 211.6949 14.52173283 51124
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Fig. 6 TLE for Cryosat-2

The TLE are analyzed by a text parser in MATLAB written for this project so that the SGP4 Simplified Perturbations Model can be used to propagate the orbit.

The Earth-Centered-Earth-Fixed (ECEF) and The World Geodetic System from 1984 (WGS-84) are used to locate points with respect to the Earth. ECEF is rectangular and its axes are fixed to the Earth. WGS-84 of latitude, longitude, and altitude is similar to a spherical coordinate system, but it is based on the oblate spheroid model of the Earth. Both systems are centered at the center of mass of the Earth. Both systems are used interchangeably. It is important to note that these coordinate systems rotate with the Earth through inertial space; therefore they are not themselves inertial (for the purposes of describing spaceflight). Distance measurements are in meters, and angular measurements in degrees.

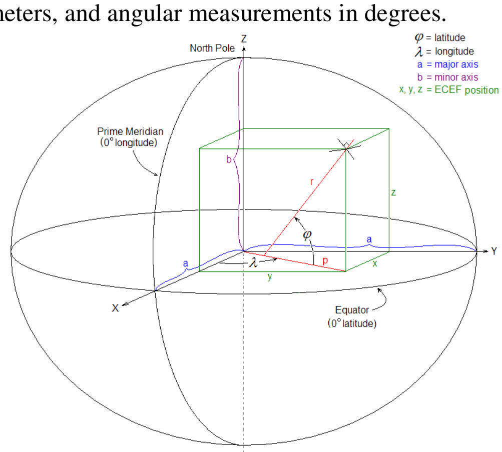

Fig. 7 Earth Coordinate Systems [5]

1) ECEF: The X-axis extends from the center of the Earth through the intersection of the Equator and the Prime Meridian. The Z-axis extends from the center of the Earth through the North Pole. The Y-axis is added such that the ECEF is right-handed (i.e. y^_ECEF=z^_ECEF×x^_ECEF). Position is expressed as a three-dimensional rectangular coordinate (x,y,z). The geometric interpretations of the ECEF components are shown in green in Fig. 5.

2) WGS-84: WGS-84 provides an internationally recognized standard for global navigation and positioning. Position is expressed as two angles (latitude φ, and longitude λ) and once distance (altitude above sea level, in meters). The Earth is not spherical; it is more accurately modelled as an oblate spheroid. This model of the Earth is obtained by rotating an ellipse about the Z-axis of ECEF. The ellipse has a major radius (i.e. the distance from the center of the Earth to any point on the Equator; distance a in) of 6,378.137 km, and a minor radius (i.e. the distance from the center of the Earth to each Pole; distance b in) of 6,356.752 km.[4]

3) ISO 6709:1983: This is the standard representation of latitude, longitude and altitude for geographic point locations. WGS84 coordinates are converted to latitude, longitude and altitude, which are represented exclusively under the ISO 6709:1983 standard.

4) IEEE 754-2008: This standard was used to accomplish the floating point processing necessary for attitude control system after reading the data from the magnetometer .

TABLE I
MICROMAG3 SPECIFICATIONS

Sensor Name	Voltage (V)	Typical Current (mA)	Units/LSB	Interface
MicroMag3	3 or 5	<.5	.032 µT	SPI

MicroMag3 magnetometer has magneto-inductive sensors oriented along each axis. [6] The magnetometer has an SPI interface, draws very little current, and has a high maximum resolution.

Our commands to the magnetometer specified the axis to measure (X, Y, or Z). Magneto-inductive sensors measured the frequency of an LR relaxation oscillator whose inductance depends on the external magnetic field, by the nonlinear permeability µ(H) of the core material. [6]

We accomplished the floating point calculations necessary by enabling floating point math in AVR Studio IDE. We used Atmega644 as our satellite`s microcontroller. This microcontroller is an 8-bit MCU and the float types are 32-bit IEEE 754. The floating point numbers are either slightly under-estimated, or slightly over-estimated, to sums of powers-of-two. The value of an IEEE-754 number is computed as: sign * $2^{exponent}$ * mantissa. [7]

During our design we considered using an external Floating Point Unit (FPU) but we decided not to since the calculations were sufficient. An FPU would help for fewer clock cycles with higher precision results.

B. Communication System

The communication system allowed us to deliver and exchange information between the satellite and the earth station; receiving and sending data or commands. A realistic and reliable communication system was chosen since the wireless communication system was important in our project.

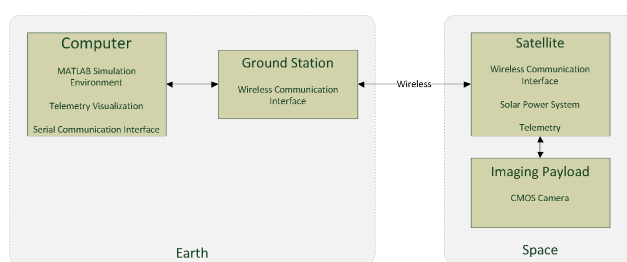

Fig. 8 High Level Block Diagram

We decided that the RF transmitter/receiver module is the most appropriate communication method and suitable component for the design. One of the advantages of using

315/433MHz RF transmitter/receiver module was that these frequency bands were registered and reserved for CubeSat satellite communication; amateur radio stations. In addition to that the real satellite uses the radio frequency (RF). Two pairs of RF communications were used in our project. It is implemented on both satellite and ground station to provide uplink and downlink channels. The Atmega644`s two USART ports are used for interfacing with the satellite with the RF transmitter/receiver. We used an USB TTL Serial Cable for interfacing the base station pc with the RF transmitter/receiver. The data exchange between transmitter and received is minimized by usage of frames and piggybacking of information in the frames. Cyclic redundancy check is used for error detection.

Commanding to the satellite is protected with a password. The internal watchdog timer of the Atmega644 keeps track of all the operations. The watchdog timer waits controller to send an acceptable signal within a time. The timely signals inform the watchdog that microcontroller is running fine. The satellite software was designed in a modular manner.

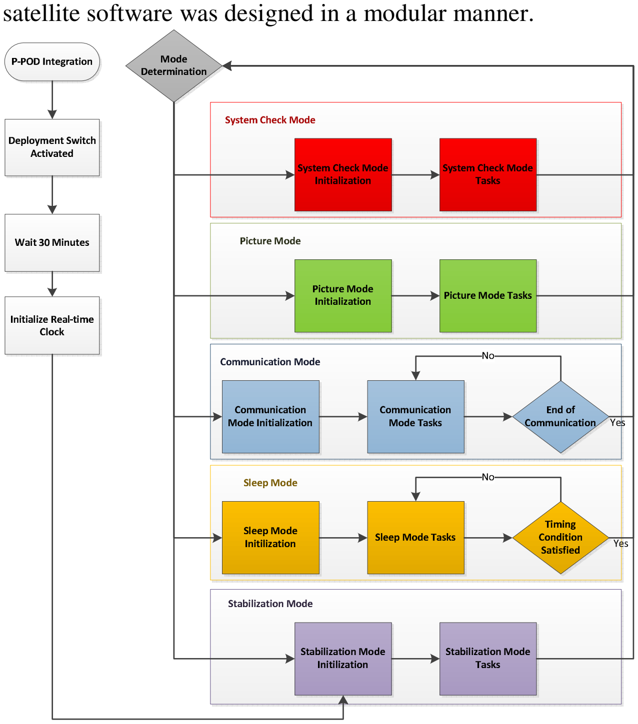

Fig. 9 Modular Design

1) IEEE 802.15.4c: IEEE 802.15.4c is an amendment for an alternative Physical Layer Extension to support the 314–316 MHz and 430–434 MHz communication bands. [8] This section presents adaptation of IEEE 802.15.4c Physical Layer (PHY) and Medium Access Control (MAC) to the wireless communication between the base station and the satellite in our project. PHY layer is used to provide a data transmission service. It manages the physical RF transceiver. MAC layer is used for point-to-point delivery between the nodes. It manages access to the physical channel.

The hardware platform of the wireless communication is the RF transceiver circuit. The circuit provided the basic functionality of PHY layer and MAC layer. The circuit has low power consumption and small size. The interface circuit between the MCU and the RF chips is the route which MCU controls the RF chips and data exchange between the MCU and the RF chips. The power consumption of 315/433MHz RF transmitter/receiver module is 15mA typical and 18mA Max.

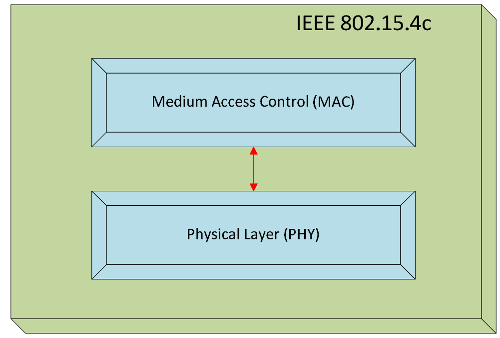

Fig. 10 Coverage of the standard

The communication mode is executed when the estimated communication time (communication window) is read from the clock. After the satellite receives a beacon from the base station the data transfer begins. The physical layer decides if the channel is busy. The transmission queue is up to seven MAC frames (based on the standard [8]). If a frame is lost, it is sent again till approval for receiving is received. The received data is rejected if it is not compliant to the IEEE 802.15.4c standard frame, after a CRC check. The sender is requested to repeat the transmission if any error is detected. The implementation is based on sequential programming. All of the primitives were executed sequentially in the application layer. Interruptions were used to guarantee that synchronization frames were sent and received in timely manner. The satellite exits the communication mode when it stops receiving messages from the base station for longer than a timeout time.

IV. Testing

This section briefly mentions about the tests that were made to the systems that was mentioned in the previous section.

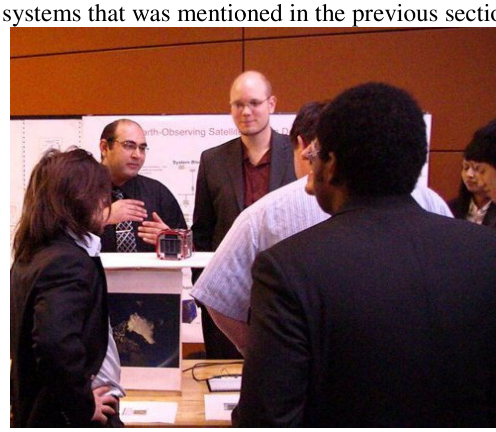

Fig. 11 Demonstration of the satellite and the simulation

A. *Attitude Control System Test*

Due to the extremely low acceleration induced by the coils, it was difficult to test the ACS in the atmosphere. In a frictionless environment angular acceleration will surely be observed, but any test setup did not provide sufficiently small friction to actually see the coils behaving as expected.

The orbit propagator was tested in the MATLAB program and yielded acceptable results. The TLE for the International Space Station (ISS) were loaded into the application and the position was within 100 km of the position reported by NASA's online tracking tool [9].

Part of the ground station user interface showing the satellite name and ground track (red) and the communication window (green) is given in Fig. 8.

Fig. 12 Part of the Ground Station User Interface

B. *Communication System Test*

We tested our data by sending command frames from base station to the satellite and receiving data frames from the satellite. The wireless communication worked with no error at 1200 bps. A typical CubeSat is in communication range of the ground station for approximately 40 minutes per day with a theoretical maximum data rate of 1200 bps. For this reason we decided 1200 bps would give us a realistic communication system. The range for the 1200bps was 13 feet with no error. When we increased the distance we started to receive errors. Signals from other sources and the frames with errors were ignored by the satellite and the base station. We were able to successfully send commands and receive data from the CubeSat.

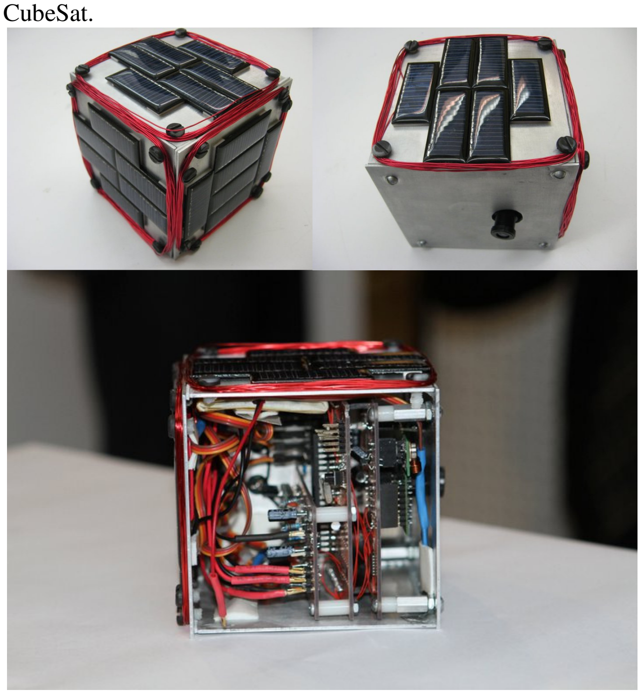

Fig. 13 ConSat-0 from behind, front and the interior view

V. CONCLUSIONS

In conclusion, we have successfully built an earth observing picosatellite and simulated an polar observing mission. The use of ECEF, WGS-84, ISO 6709:1983, IEEE 802.15.4c and IEEE 754-2008 industry standards helped us to make better and more professional design decisions. ECEF, WGS-84 and ISO 6709:1983 were used for detecting the satellite position in the Attitude and Orbit Determination and Control System. IEEE 754-2008 was used for floating point processing necessary for attitude control. IEEE 802.15.4c was consulted for the design of the communication system.

This project delivered a non-spaceworthy implementation of an Earth-observing CubeSat. The project can be further developed for building a version with military and space grade components for an actual space mission.

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