MeznSat: A CubeSat for Greenhouse Gases Monitoring and Algal Blooms prediction

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ABSTRACT

MeznSat is a 3U CubeSat that will carry a Short-Wave Infra-Red (SWIR) spectrometer as its primary payload, with the aim of deriving Carbon Dioxide (CO\textsubscript{2}) and Methane (CH\textsubscript{4}) and concentrations in the atmosphere by making observations in the 1000–1650 nm wavelength region. The satellite is planned for launch in the end of 2019. The primary payload is Argus 2000 which is a miniature, low-cost, space-qualified SWIR spectrometer that operates in the SWIR bands and showcases flight heritage. The secondary payload will be an RGB camera with SXGA resolution that will allow post-processing to achieve the high geolocation accuracy required for the spectrometer. This setup of using a combination of visible and SWIR bands makes it a unique CubeSat mission that will generate a very interesting dataset to explore atmospheric correction algorithms which employ SWIR data to process visible channels. In addition, the collected data will be used to explore the performance of this particular sensing scheme, to estimate the concentration of nutrients in the coastal waters of the Arabian Gulf and investigate the feasibility of using the concentration of nutrients as a proxy to predict algal blooms.

INTRODUCTION

Climate change has widely been attributed to the increase in greenhouse gases in the atmosphere as a result of human activities. The impacts of climate change are expected to include shortage of water quantity and quality in most arid and semi-arid areas, and low agricultural productivity throughout the tropics and subtropics, accompanied by damage to ecosystems and biodiversity in these areas, and changes in forests and other ecosystems. CO\textsubscript{2} and CH\textsubscript{4} are the two most prevalent Greenhouse gases. Even though CH\textsubscript{4} does not remain as long in the atmosphere as CO\textsubscript{2}, it is approximately 21 times more heat-absorptive than CO\textsubscript{2} per unit of weight. This property makes CH\textsubscript{4} 84 times more potent than CO\textsubscript{2} in the first twenty years following its release. Both emissions, CO\textsubscript{2} and CH\textsubscript{4}, have to be addressed and monitored in order to effectively reduce the impact of climate change.

MeznSat is a 3U CubeSat satellite initiated and funded by the UAE Space Agency and in partnership with Khalifa University - Masdar Campus and the American University of Ras Al-Khaimah (AURAK). MeznSat is an educational/scientific satellite program with the aim of enhancing space research and education in the UAE and also provide the UAE space industry with qualified well-trained graduates through hands-on experience. The primary scientific objective of this project is aimed at exploring the performance of sensing in the shortwave infrared (SWIR) region (1000–1650 nm) to detect the levels of CH\textsubscript{4}, CO\textsubscript{2} and H2O in order to derive the atmospheric concentrations of important Greenhouse Gases (GHG). This mission follows the previous missions like CanX-2 (1), SathyabhamaSat (2), etc. and aims to generate useful datasets to be utilized by relevant government agency and educational institutions.

The secondary tentative experiment of MeznSat will investigate the possibility of detecting increase in algae using the SWIR spectrometer data. Algal blooms in the Arabian Gulf can have a detrimental effect on the economy and health in the UAE. The Arabian Gulf hosts some of the largest desalination plants in the world and most of them are located along the UAE coast line. They account for a big percentage of the potable water consumed by UAE residents and the desalination capacity of the plants is constantly increasing. However, a recent surge in algal blooms in the Arabian Gulf is threatening the optimal operation of these desalination plants, which in turn will affect water availability in the UAE (3). Efficient monitoring and early sensing of algal blooms is required to efficiently manage the operations of the desalination plants. Algal...
blooms are also threatening the water quality in the coastal areas thus becoming a health hazard. The algae produce toxins which affect the fish population. When algal blooms block vital sunlight from reaching beneficial underwater plants that provide food and a place to live and grow for fish and other animals, the ecosystem can be negatively impacted. Algae become stressed and die when they deplete the nutrient supply or move from freshwater into saltier waters. Decomposition of dying algae can reduce levels of dissolved oxygen in the water, which fish and other aquatic animals breathe. Some fish species with little tolerance for low dissolved oxygen levels may die. In addition, some algal species can cause fish kills directly either by production of algal toxins or by clogging the gills. While the possibility of algal toxins in the environment is a serious concern, the more common problems associated with harmful algal blooms are environmental damage and the impact on recreational activities and commerce due to the unsightly green scum and accompanying unpleasant odour. An efficient and early sensing system is required to facilitate swift response.

CUBESAT BUS

Structure

MeznSat is standard 3U CubeSat size with body-mounted solar panels on all it sides. On the X-minus axis, an antenna deployment system is mounted. A number of five through holes on Y-axis and Z-axis will accommodate for the required optical sensors (3 for ADCS system and 2 for payloads). The antenna system consists of two-dipole antenna (UHF and VHF). A deployable magnetometer will be mounted on the Y-minus axis of the satellite. The solar panels substrate is made of typical PCB FR4 and mounted onto the structure via screws mount. A total of 20 triple junction solar cells are mounted onto the satellite.

<table>
<thead>
<tr>
<th>No.</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deployable ADCS Magnetometer</td>
</tr>
<tr>
<td>2</td>
<td>Spectrometer (Payload)</td>
</tr>
<tr>
<td>3</td>
<td>Battery Board</td>
</tr>
<tr>
<td>4</td>
<td>Main Structure</td>
</tr>
<tr>
<td>5</td>
<td>3-axis Reaction Wheel</td>
</tr>
<tr>
<td>6</td>
<td>3-axis ADCS Board with Sun Sensor, Earth Sensor, Magnetorquer, Gyro, CubeCoil</td>
</tr>
<tr>
<td>7</td>
<td>Interface Board 1</td>
</tr>
<tr>
<td>8</td>
<td>Interface Board 2</td>
</tr>
<tr>
<td>9</td>
<td>ADCS Star Tracker</td>
</tr>
<tr>
<td>10</td>
<td>RGB Camera (Payload)</td>
</tr>
<tr>
<td>11</td>
<td>EPS Board</td>
</tr>
<tr>
<td>12</td>
<td>OBC Board</td>
</tr>
<tr>
<td>13</td>
<td>Communication Board</td>
</tr>
<tr>
<td>14</td>
<td>Deployable Antenna</td>
</tr>
</tbody>
</table>

Figure 1. MeznSat Internal Hardware Configuration

Command and Data Handling

The iOBC from Innovative Solutions In Space (ISIS) (4) was chosen as the best fit for our requirements after evaluation and analysis. It is flight proven and has a low power (1.0V core voltage) processing unit based on ARM9 with a speed of 400 MHz. Furthermore, it comes a customizable daughter board is available that provides extra interfaces for the subsystems, and additional subsystem support and mission support software. It provides a wide range of interfacing and memory options.
Electrical Power Subsystem

Typically, power generation is realized using high efficiency triple junction solar modules and storage through batteries and/or flywheels. Power converters and switch arrays are responsible for distributing the available power to the subsystems/loads.

To calculate the power generation of a satellite a number of parameters need to be defined regarding the satellite’s configuration (area of solar modules per side, efficiency of solar modules), attitude and orbit. The simulations were conducted taking into account preliminary designs and analysis of subsystems related to the aforementioned parameters. Table 2 provides information about the simulation parameters.

Power generation simulations were conducted utilizing NASA’s General Mission Analysis Tool (GMAT) and Matlab. GMAT simulated the satellite’s orbit propagation and attitude characteristics while Matlab was used to post-process the acquired data and calculate the power generation profile. It has to be noted that the albedo effect was not considered. Figure 3 demonstrates the instantaneous power generation profiles during 1 orbit. The average power of the orbit is 3.54W.

<table>
<thead>
<tr>
<th>Table 2. Power generation simulation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar panel max power</td>
</tr>
<tr>
<td>Solar panel allocation per side</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Orbit A</th>
<th>Alt=450km, INC=98°, RAAN=150°, AOP=0°, TA=180°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Epoch</td>
<td>22 Jul 2019 11:30:00</td>
</tr>
<tr>
<td>Attitude</td>
<td>Nadir pointing (+y)</td>
</tr>
</tbody>
</table>

Figure 2. System Architecture Diagram

Communication Subsystem

Communication Subsystem provides the uplink and downlink communications between the spacecraft and ground stations. It consists of UHF/VHF band transceiver. UHF and VHF transmitter has a dedicated dipole antenna. TRXVU radio subsystem from ISIS was selected (5).
UHF/VHF Transceiver System

UHF transmission system guarantees the transmission of telemetry and image data from satellite to the ground station. It consists of a baseband modulator module and a transmitter module. The baseband modulator is working at 9.6 kbps data rate using BFSK modulation technique. The frequency range for transmission carrier is from 430MHz to 450MHz.

VHF receiving system receives of telecommand from ground station to the satellite. It consists of a baseband demodulator module and a receiver module. The baseband modulator is working at 1.2 kbps data rate using AFSK modulation technique. The frequency range for transmission carrier is from 130MHz to 150MHz.

UHF/VHF Antenna System

Spacecraft antenna system consists of two antennas; UHF and VHF dipole antennas. This antenna has individual connection direct to the transmitter for dipole antenna and receiver has dedicated interface to other set of dipole antenna.

Attitude Determination and Control Subsystem

Attitude Determination and control Subsystem (ADCS) is intended to determine the orientation and angular velocity of the spacecraft, and control it to reach the desired orientation and angular velocity to meet the mission requirement.

The ADCS is responsible for detumbling the satellite after deployment, pointing the satellite in a favorable attitude to meet the mission requirements as well as for recovering it from any spin-ups during the mission. The ADCS system for this system will consist of three parts: the attitude determination system, the attitude control system and the attitude-processing computer.

The CubeADCS (6) unit from CubeSpace uses the following sensor measurements to estimate the attitude of the satellite:

- Magnetometer, Coarse sun sensors, MEMS rate sensor(s)
- Fine Sun sensor, Fine Earth sensor
- Star tracker

Estimation and control algorithms are run on the ADCS on-board computing unit that is included in the CubeADCS. It uses magnetorquers and three reaction wheels to actuate the satellite’s attitude. The CubeADCS unit consists of up to four integrated PC104-standard PCBs and several peripheral components, which are to be mounted separately. A basic diagram of a complete CubeADCS solution with all peripheral components is shown in Figure 4.

![Figure 4. MeznSat ADCS (image courtesy of: CubeSpace)](image)

Primary Payload

The scientific objective of this mission is to explore the performance of sensing in the shortwave infrared (SWIR) region and specifically in the range of 1000–1650 nm, to detect the levels of Methane and Carbon Dioxide in the atmosphere.

The selected primary payload for this purpose is an Argus 2000 (7) - Figure 5 - spectrometer which is a miniature, low-cost, space-proven spectrometer that operates in the near infrared bands and measuring only 4.5 x 8 x 8 centimeters in size. Light entering the instrument is dispersed by a 300 groove/mm grating and directed onto a 256-element Indium-Gallium-Arsenide detector array cooled by a Peltier cooler to reduce dark currents.

The spectrometer covers a spectral range of 1.0 to 1.65 micrometers with a 6-nanometer spectral resolution across 100 spectral channels. Atmospheric species absorbing within the instrument’s spectral range are oxygen, carbon dioxide, water, carbon monoxide, methane and hydrogen fluoride. Argus supports integration times between 0.5 and 4.096 seconds.

![Figure 5. Argus 2000 Spectrometer](image)
Secondary Payload

The selected camera is an RGB camera developed by Tokyo University of Science which already has flight heritage (8). Main purpose of the camera is educational in order to demonstrate the process of remote sensing. The module utilizes the OV-9630 Image Sensor from Omnivision and a Microchip PIC microcontroller as an interface between the image sensor and the on-board computer (OBC). A Universal-Asynchronous-Receiver-Transmitter is provided for communication with the OBC. The key specifications of the camera module are presented in Table 3.

![Figure 6. RGB camera module](image)

**Table 3. RGB camera module specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array Size</td>
<td>1280x1024 (SXGA)</td>
</tr>
<tr>
<td>Power Requirements</td>
<td>150mW (Active), &lt;1mW (Standby)</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>0°C to 70°C</td>
</tr>
<tr>
<td>Output Formats (10-bit)</td>
<td>RAW RGB Data</td>
</tr>
<tr>
<td>Lens Size</td>
<td>1/3&quot;</td>
</tr>
<tr>
<td>Maximum Image Transfer Rate</td>
<td>15fps (SXGA), 30fps (VGA)</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1.0 V/Lux-sec</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>60dB</td>
</tr>
<tr>
<td>Maximum Exposure Interval</td>
<td>1048 x tROW</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>4.2μm x 4.2μm</td>
</tr>
<tr>
<td>Dark Current</td>
<td>28 mV/s</td>
</tr>
<tr>
<td>Fixed Pattern Noise</td>
<td>&lt;0.03% of Vp-p</td>
</tr>
<tr>
<td>Image Area</td>
<td>5.4mm x 4.3 mm</td>
</tr>
<tr>
<td>Package Dimensions</td>
<td>.56 in. x .56 in.</td>
</tr>
</tbody>
</table>

MISSION ORBIT

The lifetime of the mission is three years, which entails a minimum orbit of 450km. The actual orbit is still not determined as launch opportunities are still in discussion with launch providers. The MeznSat conceptual mission is a SSO orbit with the altitude of 450-600km and inclination more than 90 degrees in such a way that the satellite with this orbit has a nodal regression rate which is equals to Earth’s orbital rotation speed around the Sun. This conceptual mission takes into account of the consistency of operational and environmental conditions.

MeznSat orbit analysis or design is derived from the orbit mission. The requirements that drive the choice of orbit are as follows;

1. To provide an opportunity for payload operation over UAE
2. To have a reasonable number of passes or contact with the ground station over UAE.
3. To provide an opportunity to conduct a good payload operation with time constraint of 10am to 2pm local time over the ground target (UAE).
4. To comply with the mission lifetime criteria of 3 years defined by the sponsor.

The other rationale of conducting the orbit analysis is to provide an alternative feasibility or trade off study to launch the satellite from International Space Station (ISS) as a backup plan in case an SSO launch opportunity is not feasible.

**Orbit Design Analysis**

The analysis for the orbit requirements for MeznSat covers the following:

1. Orbit Lifetime – To calculate the lifetime of MeznSat in orbit operation.
2. Coverage time – To calculate the coverage time for MeznSat during contact with the ground station.
3. Revisit – To calculate the MeznSat revisit over UAE in 1 day
4. Payload operation opportunity – To calculate the opportunity for imaging over UAE

**Orbit Lifetime**

The lifetime for the satellite is analyze from the following orbit altitude and inclination

1. ISS orbit - Circular orbit, Altitude 400km, 51° inclination.
2. ISS orbit - Circular orbit, Altitude 450km, 51° inclination.
3. Sun synchronous orbit, Altitude 450km, 97° inclination.
4. Sun synchronous orbit, Altitude 500km, 97° inclination.
5. Sun synchronous orbit, Altitude 550km, 97° inclination.

Sun synchronous orbit, Altitude 650km, 97° inclination.
Figure 7. Orbital Lifetime Summary

Payload Coverage Analysis

Basic Assets/Sensors properties:
1. RGB Camera:
   - Sensor Type: Rectangular
   - Vertical Half Angle: 20 degrees
   - Horizontal Half Angle: 20 degrees
2. Spectrometer:
   - Sensor Type: Rectangular
   - Vertical Half Angle: 0.075 degrees
   - Horizontal Half Angle: 0.075 degrees

Basic Region Properties:

The region consists of the land and EEZ part of the UAE. The following analysis was performed taking into account the constraint that the sensors will only cover the area around the time 10am to 2pm.

Retrievals of GHG concentrations will be made through inversion of radiance measurements by means of radiative transfer modeling. For the first products of the mission we intend to follow the same processing steps implemented for processing CANX-2 data which tested the same payload successfully (9).

A detailed calibration plan will be devised for the instrument to convert the digital counts to accurate radiance measurements by utilising standard reflectance targets with accurately identified reflectance values. A lab spectrometer will be extensively used for cross-validation of the instrument calibration.

The potential for algal blooms comes from nutrient pollution, an overabundance of the essential plant nutrients nitrogen and phosphorus. These elements enter waterways from point sources (such as industrial and wastewater treatment plant discharges), non-point sources (such as septic tanks and storm water runoff, urban areas and residential areas), and from nutrient-enriched rainfall or dust storms which occur frequently in the region. When the concentrations of Nitrogen and Phosphorus increase in a water body; the right combination of temperature, sunlight and low flow can trigger an algal bloom. Though nitrogen and phosphorus occur naturally and are essential plant nutrients, an overabundance of these nutrients can cause
significant imbalances in the water body’s ecology, and blooms are one symptom.

The current research is aimed to explore the performance of the sensing in the shortwave infrared (SWIR) region (1000–1650 nm) in combination with the RGB camera to estimate the concentration of total suspended matter (as a proxy for nutrients in water) in the coastal waters of the Arabian Gulf to predict an algal bloom in advance to facilitate precautionary measures.

REFERENCES


