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PICASSO: A State of the Art CubeSat

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ABSTRACT

PICASSO is a highly ambitious 3U CubeSat science mission with the objective of studying ozone distribution in the stratosphere, characterizing the air temperature profile up to the mesosphere, and measuring the electron density and temperature in the ionosphere. In order to achieve these objectives, PICASSO will fly a payload comprising two main instruments, one being a sweeping Langmuir probe and the other a visible and near-infrared hyper-spectral imager.

This paper discusses the science instruments and objectives, and highlights the importance of these data to the science community. In addition, the demands on the spacecraft platform resulting from the payload requirements are explored, demonstrating the spacecraft meets these requirements within the limitations of a 3U CubeSat.

PICASSO is an exciting CubeSat mission that has the potential to set a benchmark for performance of tiny spacecraft whilst also proving to the space community in general that CubeSats do offer an opportunity to achieve demanding science objectives at low cost.

BACKGROUND AND INTRODUCTION

PICASSO is a scientific CubeSat-based project initiated by the Belgian Institute for Space Aeronomy (BISA) in 2010. It is currently administered by the European Space Agency (ESA) within the frame of the General Support Technology Programme (GSTP) and of the Technology Research Programme (TRP). In addition to BISA, which acts as project prime and scientific principal investigator (PI) of the two instruments, the PICASSO consortium includes three European partners:

- Clyde-Space Ltd (UK), in charge of the platform development, of the payload integration, of the ground-based station and of the satellite control and monitoring;
- VTT (Finland), in charge of developing the VISION instrument;
- The Centre Spatial of Liège (CSL, Belgium), responsible for the technical coordination and for the PA/QA aspects of the project.

The satellite is built upon a 3U platform featuring four deployable solar panels, UHF/VHF and S-band communications, two on board computers, a high performance ADCS, and two scientific instruments for ESA-grade science data.

The scientific nature of the payload and the demanding requirements of the instruments in terms of platform performance mean that this mission is arguably one of the more advanced spacecraft with a mass below 5kg ever produced. The most demanding of these requirements come from the hyper-spectral imager (HSI). The HSI must be pointed at the Sun when entering and exiting eclipse for the purpose of imaging the atmosphere at various altitudes. This requires a highly capable attitude determination and control system so as to control the spacecraft in 3 axes whilst achieving fine pointing in both eclipse and sunlight conditions. In addition, the payload generates close to 100 MBps of data during operation which must be captured and processed on-board before being downlinked to the ground. Further still, this tiny CubeSat must generate an orbit average of over 10W in order to ensure enough power to complete the mission objectives.

In addition to the key science objectives of the mission, PICASSO aims to demonstrate the ability of small satellites to carry out actual scientific experiments – this is particularly relevant for remote sensing experiments.[1] Importantly, as an ESA mission, successfully demonstrating the ability to achieve significant science goals on a very low-cost platform would potentially open the door to ESA utilizing spacecraft of this class for future missions and applications.

MISSION OVERVIEW

The objective of PICASSO is to demonstrate the capacity of low-cost nano-satellites to perform remote and in-situ scientific measurements of physicochemical properties of the Earth's atmosphere. In addition to these, PICASSO also aims to bring the instruments and the on-board data processing components to high technology readiness levels in order for them to be incorporated in future scientific missions with a reduced risk. To achieve these goals, the satellite shall be launched into a high inclination low-Earth orbit with a lifetime of at least 2 years, embarking a miniaturized hyperspectral imager (VISION) and a Sweeping Langmuir Probe (SLP).

At LEO altitude, PICASSO will be flying through the upper layers of the ionosphere with an orbital period of approximately 94 minutes. Given its high orbital inclination PICASSO will have the opportunity to sample the ionosphere rather globally, making it a suitable platform for global ionospheric monitoring. SLP is an upgraded version of the traditional Langmuir probe. It is designed specifically for electron density measurements at high space and time resolution. It is based on four cylindrical probes whose electrical bias potential is periodically swept across the spacecraft potential and well into the electron saturation region so as to be able to infer electron temperature and density. At the same time, precautions are taken to avoid SPL operation leading to abnormal spacecraft charging.

The other instrument, VISION, is a tunable spectral imager active in the visible and near-infrared. It primarily targets the observation of the Earth's atmospheric limb during orbital solar occultation. By assessing the radiation absorption in the Chappuis band for different tangent altitudes, the vertical profile of the ozone will be retrieved. A secondary objective of VISION is to measure the deformation of the solar disk so that stratospheric and mesospheric temperature profiles may be retrieved by inversion of the refractive ray-tracing problem.

These instruments are hosted on a 3U structure with a high strength to weight ratio, which was designed with rigidity in mind. The structure supports all internal subsystems as well as four 2U deployable solar panels with the SLP probes mounted at their extremity, deployable dipole UHF/VHF antennas, and an S-band patch antenna. It provides apertures for all optics including fine Sun sensor, star tracker and the VISION payload – see Figure 1. The system-level design will be described in more detail in the following sections.

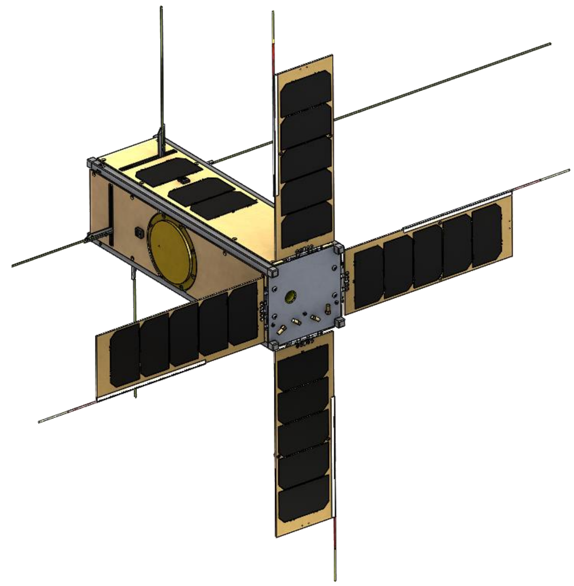

Figure 1 – CAD rendering of the PICASSO CubeSat illustrating deployed solar panels, UHF/VHF antennas and externally mounted subsystems.

SYSTEM DESIGN

The stringent requirements imposed by the science experiments onboard PICASSO place high demands on the system design, particularly in regards to attitude control and power. The following sections describe the subsystems in more detail, and outline our approach to resolving these challenges.

VISION

VISION is a hyper-spectral imager in the visible and the near-infrared domain, between 430 and 800 nm. It is capable of taking 2D snapshot at freely selectable wavelengths within this range; the spectral selection is performed by a tunable Fabry-Perot Interferometer (FPI), the basic concept of which is shown in Figure 2.

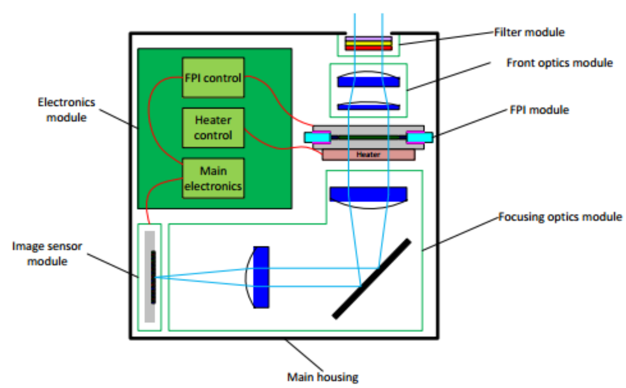

Figure 2 - VISION functional diagram

VISION's main goal is the observation of the Earth's atmospheric limb during orbital solar occultation. By measuring the light absorption in the Chappuis band, vertical profiles of ozone concentrations can be retrieved.

Its second target is to assess the refracted Sun shape in order to retrieve stratospheric and mesospheric temperature profiles by inverting the ray-tracing problem. Full spectral scan observations of nightglows and polar auroras are also foreseen if the dynamic range of the instrument allows it.

Figure 3 illustrates the general principle of a measurement by solar occultation. The Earth's atmosphere is represented by the light blue area around the picture of the Earth, the orbit of the S/C by the black circle and the Sun by the yellow symbol. Somewhere in between A and D (in this image the S/C is travelling clockwise), the Earth appears at one side of the imager. It moves towards the opposite side until it fills the entire image (this occurs at sunset; sunrise would create the opposite effect). In the atmosphere the sunlight beam is refracted and it bends towards the Earth. From the imager perspective, refraction leads to two phenomena. Firstly the Sun's apparent position is displaced away from the Earth, as if the Earth was repelling it.

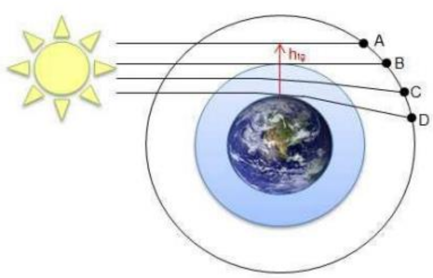

Figure 3 - Solar occultation principle

Secondly, as illustrated in Figure 4, the apparent shape of the solar disk shrinks along the vertical dimension (relative to the Earth image). This deformation comes from the fact that rays emanating from the bottom of the Sun image propagate into denser atmospheric layers than those emanating from top. By solving the inverse ray-tracing problem of the photons propagation in the atmosphere, the mesospheric and stratospheric temperature profiles can be retrieved. Spectacular results have recently been obtained by the SOFIE instrument aboard the Aeronomy of Ice in the Mesosphere (AIM) spacecraft by detecting the edges of the solar disk and the related refraction angle.[2] Here we expect to improve the method by making use of the full solar disk.

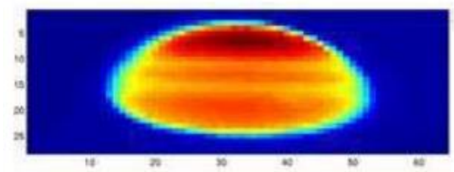

Figure 4 - Sun Image Flattening

The solar brightness is attenuated by scattering, absorption and diffusion processes along the optical path in the atmosphere. By studying the attenuation spectrally, profiles of physical properties and chemical components in the atmosphere can be retrieved. Results from the numerical simulation of the attenuation of the photon number at different tangent heights are illustrated in Figure 5 – here, the upper curve corresponds to a 50 km altitude, decreasing in 5 km increments down to a 5 km altitude, which is represented by the lower curve. The photon depletion around 600nm corresponds to photon absorption by the ozone in the so-called Chappuis band. Resolving it gives access to the ozone profile.

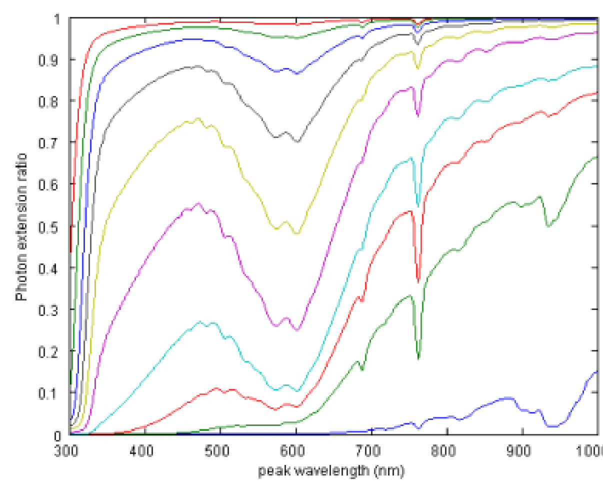

Figure 5 - Spectral photon depletion (5 km to 50 km altitude in 5 km increments – lower to upper curve)

SLP

The principle of SLP's measurement is based on conventional Langmuir probe theory.[3] By sweeping the potential of the probes with respect to the plasma potential, the instrument measures the current in the three regions: ion saturation, retardation and electron saturation regions. The typical characteristics of such a probe are illustrated in Figure 6.

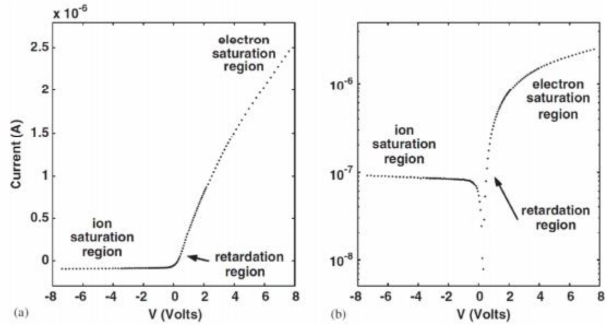

Figure 6 - Typical Langmuir probe characteristics in linear (left) and logarithmic (right) current axis

The ion density is derived from the ion saturation region, where the potential of the probes is sufficiently negative to repel electrons and attract only true ions. The electron temperature and S/C potential are retrieved from the retardation region, where the potential of the probes is close to that of the plasma so that both ions and electrons are attracted. The electron density is derived from the electron saturation region, where the potential of the probes is sufficiently positive to repel ions and attract only electrons.

In nominal mode SLP sweeps the potential of the probes from -7V to +7V with respect to the plasma potential in order to retrieve the electron density and temperature, together with the S/C potential and the ion density (when it is large enough). In another mode, the instrument measures only in the electron saturation region at a higher rate, measuring electron density with better spatial resolution. This operating principle is more advanced than the idea of using 4 probes at four different fixed bias potentials in the electron saturation region[4], since it allows a more detailed analysis and permits the determination of electron temperature as well. In addition, with this operating principle, there is no need for an electron gun.

The probes are thin cylindrical titanium rods, mounted on the deployable solar panels, which act as deployable booms. This configuration ensures that at least one probe is out of the S/C's wake at any time, in addition to providing redundancy.

Attitude Determination & Control System (ADCS)

The key pointing requirement for this mission is to ensure that the VISION instrument stays aligned to the Sun during the entire duration of the Sun's occultations by the Earth's atmosphere. This requires the pointing accuracy of VISION relative to the sun to be 1 degree or better. To meet this requirement, the ADCS must be able to have sufficient pointing knowledge and control performance to provide this resolution of control. In addition, the alignment between the ADCS and VISION must be measured and corrected for.

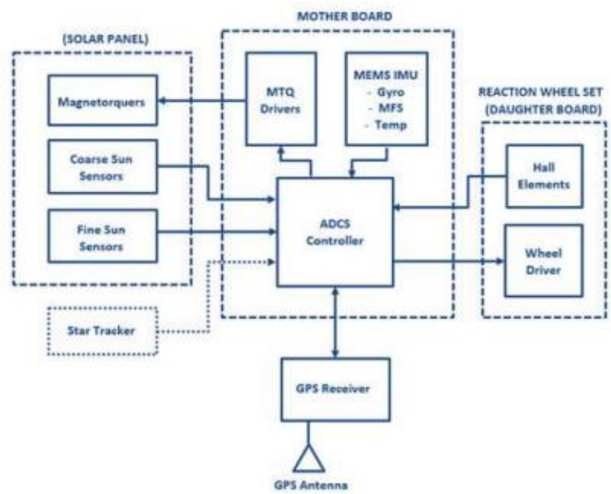

Figure 7 - ADCS architecture

The ADCS subsystem architecture is illustrated in Figure 7. It includes:

- ADCS Motherboard (ADCS MB)
- Reaction wheel set (RWS)
- Fine Sun sensor (FSS)
- Coarse Sun sensors (CSS)
- Star tracker (STT)
- Magnetorquers (MTQ)
- GNSS system (GPS).

The ADCS motherboard benefits from the heritage of the ADCS board that has successfully flown on UKube-1. An FPGA-based processing architecture has been specifically selected to ensure a system that is more robust to radiation events. The central Actel FPGA interfaces to the sensors and actuators, while a secondary processor acts as a watchdog, can place the spacecraft into a safe mode and can also be used to provide emergency detumbling of the spacecraft should the need arise.

The ADCS will utilize the standard Clyde Space three-axis CubeSat reaction wheel system. Each reaction wheel is capable of providing a torque of up to 2mNm; however, for this mission the torque is limited to 0.23mNm in order to enable a finer pointing control. The wheels will provide a total angular momentum of 3.53 mNms in an angular velocity range of ± 7500RPM.

The FSS is mounted on the Sun pointing face of the satellite and is used as the primary sensor during the sunlit period of the orbit, while the star tracker is used in support of orientation determination during eclipse. The magnetometers are used to sense the magnitude and direction of the magnetic field on the body of the CubeSat.

Voice coils embedded into the solar panels represent the MTQ. These devices generate a magnetic dipole that interacts with the Earth's magnetic field, generating a mechanical torque. These actuators are used to detumble the spacecraft, to provide coarse pointing acquisition, and to manage the RWS angular momentum.

The ADCS is validated during ground testing using Clyde Space's Hardware-In-the-Loop (HIL) simulator. The complete HIL set-up is a high fidelity, six degrees of freedom, spacecraft dynamical model interfaced directly with the ADCS hardware on which the attitude control algorithms run. The set-up allows validation of the autonomous attitude control software and hardware for all phases of the mission.

Critically, real data from the sensors and actuators are used to simulate the entire mission. This allows many of the un-modelled dynamics that, because of the presence of unknown parameters, do not have clear mathematical formulations. These can include interference on the magnetometers from magneto-torquer output and magnetometer reading; reaction wheel velocity and gyros output; sensor noise and pointing accuracy; and others. Consequently, the use of this system level HIL test vastly reduces the impact of 'non-ideal' operation of system hardware on the performance of the ADCS control algorithms, and therefore de-risks the potential for attitude control problems on-orbit.

Electric Power System (EPS)

Power conditioning is carried out using an off-the-shelf third generation Clyde Space (CS) EPS (Figure 8), with 3 maximum power point tracking battery charge regulators providing protected primary power lines: 3.3V at 4.5A, 5V at 4.5A, 12V at 1.5A, and unregulated Battery V at 4.5A. The system also incorporates the flight activation system of separation microswitches, and the flight interface with an external 5V USB charge and remove before flight pin. It also incorporates 10 power distribution switches to control the loads. The EPS board will be powered throughout the orbit, with a nominal consumption of 200 mW.

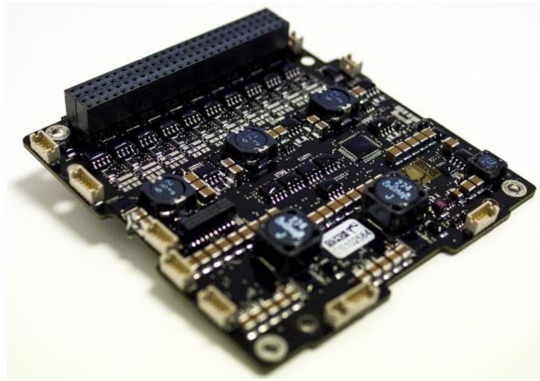

Figure 8 - Clyde Space EPS Board

The EPS also makes use of a 30Wh battery – another CS standard product with spaceflight heritage on numerous missions. Based on Lithium Polymer technology, the battery cells are arranged 2S3P, with charging EoC voltage of 8.2V.

During sunlit periods, the solar panels shall generate power to run the platform and charge the battery. A modified version of the standard CS product, four 2U deployable solar panels are mounted to the structure on their short edge. Their deployed configuration is shown in Figure 1. These panels host the SLP probes whose fixtures run alongside the solar cells. Body-mounted solar panels are also used to generate power from Earth's albedo and to maximize power generation during tumbling.

In most cases, deployable solar panels would necessitate the use of a larger EPS variant, with a daughterboard featuring additional BCRs to accommodate the additional solar panels. However, given the complexity of the platform design, volume within the spacecraft is at a premium. To address this, the solar panels will feature a custom string configuration and harnessing solution in order to eliminate the need for the additional daughterboard within the CubeSat stack.

Command and Data Handling (CDH)

There are two computers onboard PICASSO: the On-Board Computer (OBC) and Payload Computer (PLC). The OBC is the primary intelligence board and manages spacecraft operations. The PLC is dedicated to controlling the payloads and managing their data all the way to downlink.

The VISION instrument produces vast quantities of data, approximately 8GB per observation. Transmitting the raw data in its entirety to the ground is infeasible with the anticipated link budget, so a high-performance secondary computer is incorporated on board, dedicated to processing the payload data prior to transmission.

The PLC uses a Xiphos Q7S processor card adapted for a CubeSat form factor, accommodating a Xilinx Zynq-7020 all-programmable system-on-chip with a dual-core ARM Cortex-A9 core clocked at 766 MHz. The card provides 512+256 MB of low power RAM and up to 32GB of non-volatile storage on SD cards. Typical power consumption for the PLC is 1W.

Communications (COMM)

The satellite's communication system is composed of two radios: The VHF/UHF Transceiver (VUTRX) which is mainly dedicated to Telemetry and Telecommand (TMTC), and the S-band Transmitter (STX) for high data-rate payload data downlink. The radios are connected to their respective antennas (deployable dipoles for the VUTRX, patch for the STX) and will communicate with dedicated antennas on the ground as depicted in Figure 9.

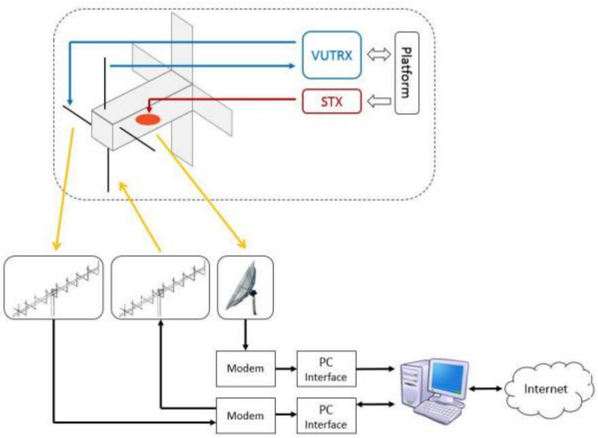

Figure 9 - Space-ground architecture

VUTRX uses an off-the-shelf CPUT UV Transceiver, providing a VHF uplink and UHF downlink at 9600 bps both ways using modified CCSDS packets and multi-access protocols, providing down/uplink of 2.15MB per day. When not transmitting, the transceiver enters a Morse Code Beacon mode and broadcasts identification and basic health data for tracking. The VU Transceiver interfaces to two VU Whip Antennas deployed from the Antenna Deployment Module (ADM).

The high volume of data generated by the VISION instrument necessitates use of greater downlink capabilities than provided by the VUTRX alone. A CPUT S-band Transmitter (STX), as flown on Clyde Space's previous satellite UKube-1, was chosen to facilitate the high data-rate transfers of payload data as well as enhanced telemetry data. This provides downlink at variable rates up to 2 Mbps QPSK, utilizing the IntelSat encoding standard and modified CCSDS packets. The transmitter shall interface to a 7 dBi S-band Patch Antenna (Figure 10) located on the Earth-facing side of the satellite.

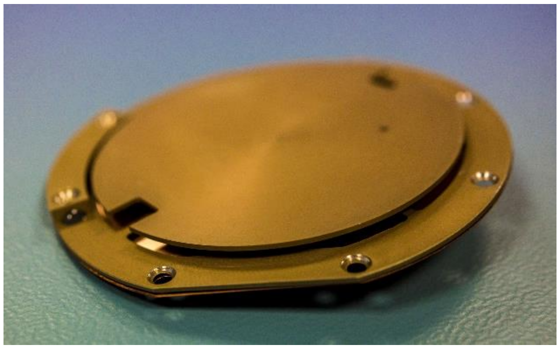

Figure 10 - S-Band patch antenna

The S-band system will enable a downlink of 102MB/day in the spacecraft's nominal sun-pointing mode. The satellite can also be re-orientated into a ground station-pointing mode, to enable a downlink of up to 204MB/day when required.

On-Board Software

The platform on-board computer runs the Bright Ascension Generation 1 Onboard Software. This component-based software has an underlying framework including OS and hardware abstract libraries, as well as support for FreeRTOS and POSIX/Linux. The software components support CS platform subsystems including integrated EPS, Battery, solar panels, ADCS, VUTRX and the standard CS payload protocol. Activities including telemetry sampling, pooling, monitoring, logging, etc., as well as automated activities that are event-, time- or orbit-triggered are also supported.

PLC software is composed of the following modules:

- Main software process
- SLP control and processing
- VISION control and processing
- GPS interface
- OBC interface
- STX control and processing.

The ground segment for PICASSO is divided into two functional areas: the Mission Operations Control and the Scientific Control Centre. The Mission control center will be supplied with the Bright Ascension Generation 1 Ground Software (GNDSW) developed in unison with the OBSW for harmonious integration. The GNDSW reaps of heritage from UKube-1.

Structure

The complexities of the mission necessitated greater latitude for customization of the structure, and flexibility during integration. After a review of the structures commercially available at the time it was determined there was nothing that would be suitable for this mission. Clyde Space therefore designed a custom CubeSat structure (see Figure 11), which has now been adapted for the wider commercial market in order to support other missions facing similar challenges.

Figure 11 - PICASSO 3U structure

The structure allows removal of individual faces whilst the inner stack remains in place. Solar panels can also be removed without the need to remove end plates. A solid section in one panel provides enhanced radiation protection for VISION. The internal ribs allow placement of the PC104 stack at any desired location within the structure. Similarly, customizable side plates permit the positioning of an antenna deployment module at any required location within the CubeSat.

This structure is also very light, particularly given its strength, weighing 332g including rails, end plates, ribs, rods, L-pieces and standoffs.

Ground Segment

Clyde Space is constructing a Ground Station (GS) at their new headquarters in the center of Glasgow, Scotland, which will be used for PICASSO mission operations. The ground station will be composed of a pair of UHF and VHF Yagi-Uda type antennas capable of both uplink and downlink as well as a 3-meter mesh dish for S-band downlink operations. The ground station will be capable of tracking satellites using orbit prediction from TLEs, and will be set up for fully autonomous up/downlink operations to maximize the use of passes.

Summary

PICASSO is an ambitious 3U CubeSat implementing a science mission aimed at studying ozone in the stratosphere, the air temperature profile up to the mesosphere, and the electron density and temperature in the ionosphere.

Its hyperspectral imager, VISION, places significant demands on the design of the spacecraft, requiring a strict pointing accuracy and generating vast quantities of payload data. This has posed significant challenges to the design of a 3U CubeSat. However, these requirements are met with an innovative platform design, incorporating: an advanced ADCS, providing a pointing accuracy of +/- 0.5 degrees and proven through extensive Hardware-In-the-Loop ground testing; a high data-rate S-band downlink, enabling transmission of up to 204MB per day; a next-generation CubeSat structure, allowing mission-specific customization; a dedicated payload computer, to process and compress payload data for transmission; customized deployable solar panels, providing significant power generation in addition to enabling a minimized power system volume; all whilst retaining a cost-effective design with significant flight heritage amongst the spacecraft's critical subsystems.

PICASSO is a next-generation CubeSat, amongst the most advanced spacecraft built within the 3U class to date. The mission will provide valuable scientific data from complex instruments, and will serve as an indicator of the capabilities and value of a modern CubeSat mission, in addition to providing valuable Lessons Learned for future platform designs. As such, PICASSO will serve as an ESA in-orbit-demonstrator of CubeSat technology and a trailblazer for small science missions.

Acknowledgments

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