DUTHSat: A Greek QB50 nano-satellite for Upper Atmosphere Studies

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Abstract

The Laboratory of Electromagnetism and Space Research of the Democritus University of Thrace (DUTH/SRL) has been selected to join the QB50 European initiative for the launch of 50 nano-satellites in the upper atmosphere by January 2016. The aim is to investigate with multi-point measurements the transition region between the atmosphere and space. The 50 nano-satellites follow the CubeSat standard, where a CubeSat is a modular satellite of standardized dimensions, assembled using primarily commercial, off-the shelf components. This provides an excellent opportunity for the launch of a Greek miniaturized satellite that is entirely built by University students and engineers. Through the QB50 program a launch opportunity and part of the science payload are provided whereas the development of each CubeSat and the ground station for communications and operations are built by the host institution. In this paper we present the objectives of the QB50 mission and the status of development of the Greek QB50 CubeSat.

1. Introduction: *Towards Satellite Miniaturization*

Following the general trend in technology for "smaller, faster, cheaper" designs, there is a continuing interest in exploring the lower limit of the size of a spacecraft capable of achieving a significant mission objective. The increasingly diminutive "small" satellites range from the micro-satellites (10-100 kg) of the 1980's and '90's, to the nano-satellites (1-10 kg) of recent years, and the pico-satellites (0.1-1 kg) of the near future. This trend for miniaturization is driven in part by the large launch costs of satellites of larger mass, but also by the development time and associated costs required for developing larger and more complex satellites, with customized components and interfaces of the satellite bus.

A key development in the process of satellite miniaturization has been the "CubeSat" concept: A CubeSat is a cube-shaped spacecraft, measuring 10 cm per side with a mass of ~1kg, which offers all the standard functionality of a normal satellite, such as on-board data handling and storage by an On Board Computer (OBC), an Electric Power Subsystem (EPS) including a battery and body-mounted solar panels, uplink and downlink telecommunications (COMMS) and Attitude Determination and Control Subsystem (ADCS). Several CubeSats can be attached to form a larger nano-satellite that can carry a technology package such as an instrument or sensor, with typically 2 cubes forming what is termed a 2-Unit or 2U CubeSat, of size $10\times10\times20$ cm and with a mass of ~2 kg and 3 cubes forming a 3U CubeSat. Started in 1999, the CubeSat Project began as a collaborative effort between California Polytechnic State University and Stanford University to develop common standards and procedures for building, testing and qualifying these CubeSats. Through this standardization, the project has enabled a design of nano-satellites that reduces cost and development time, while providing increased accessibility to space through sustaining frequent and inexpensive launches. All standards, assembly procedures, integration procedures, and testing procedures have been distributed to many developers worldwide, who develop multiple Commercial-Off-The-Shelf (COTS) as well as custom-made components for a number of applications. Presently, the CubeSat Initiative is an international collaboration of dozens of universities, institutes and private firms developing nano-satellites that contain scientific, private, and government payloads. CubeSats have also become very useful as research and educational tools: Their relatively low cost means that they become affordable within the context of laboratory equipment, and their relative simplicity means that systems and engineering principles can be taught in a clear fashion with direct relevance to systems engineering, as applied to bigger aerospace projects.

Another feature of CubeSats is that they are accompanied by a standard set of launch interface specifications, which have led to the development of P-POD, the Poly Pico-Satellite Orbital Deployer, a common interface between a launch vehicle and CubeSats. A common P-POD is capable of containing and deploying three individual 1U CubeSats, or a single 3U CubeSat, providing all essential interfaces and a spring-based CubeSat release mechanism. The P-POD has lead to a simplified integration with almost any launch vehicle and its standardization greatly reduces the possibility of interference with the primary payloads of a launch, ensuring that the CubeSats will deploy reliably; this, together with its small and modular design that allows it to fit in under-utilized spaces inside a launch vehicle has greatly enhanced CubeSat launch opportunities in recent years.

2. The QB50 CubeSat Initiative

QB50 is an innovative concept that is based entirely on CubeSats: It is a project funded by the European Commission through an FP7 grant, targeting to launch a network of 50 CubeSats in Low Earth Orbit (LEO), in order to study the Earth's Lower Thermosphere. Through QB50, universities worldwide were invited to submit proposals for their Cube-

Sat design and implementation in a highly competitive call. Out of the numerous submitted proposals, 50 universities were invited to join the project and send a satellite to space. All 50 CubeSats will be launched together on a single launch vehicle, with launch currently planned for 1/2/2016. Each team is responsible to build their own spacecraft, securing their own funds, and is also expected to downlink its satellite's data and uplink commands with its own ground station, while networks of ground stations are also envisioned and encouraged, in order to enhance coverage, satellite tracking and data volumes. By the time of launch it is expected that many of the QB50 ground stations in different parts of the world will be collaborating, linking their ground stations and providing nearly continuous uplink and downlink capability for all QB50 CubeSats, but also for other future missions.

The target of all satellites will be to study in-situ the temporal and spatial variability of a number of key constituents and upper atmosphere environmental parameters. The CubeSats will be launched from the same launch vehicle at an initial altitude of ~400 km with an inclination of 98 deg. Due to atmospheric drag, the satellites will gradually decelerate, spiraling down to the lower layers of the upper atmosphere. This will enable obtaining measurements throughout the entire Mesosphere – Lower Thermosphere and Ionosphere (MLTI) region, which, as described below, is a great step forward in MLTI research. When the satellites reach the lower and denser layers, the large temperatures that will develop due to enhanced friction will eventually lead to loss of satellite functionality and subsequently to melting and the loss of surface material from the spacecraft by evaporation. This is expected to occur in the Mesosphere, at altitudes between 80 and 100 km, where all meteorites ablate due to friction with the atmosphere.

3. DUTHSat: *A Greek participation in the QB50 initiative*

The Department of Electrical and Computer Engineering of the Democritus University of Thrace has a long-term involvement in space science and technology. It submitted a proposal to join the QB50 team in 2012, and currently DUTH is officially listed as one of the participating universities (https://www.qb50.eu/index.php/community). Participation in the QB50 consortium provides the science sensors and coordination of the project, whereas each participant of QB50 needs to design and develop their own CubeSat, securing funding through institutional or national funds. In addition, each team needs to contribute towards launch costs. For DUTHSat funding for the development of the satellite was secured through a competitive proposal to the "ARISTEIA" program, which is part of the Operational Program: Education and Lifelong Learning, a research grant that is co-funded by the European Social Fund (ESF) and National Resources and managed by the General Secretariat for Research and Technology (GSRT). Furthermore, the contribution towards launch costs was sponsored by Raycap S.A., a Greek company that manufactures and supports advanced solutions for telecommunications, renewable energy, transportation and other applications worldwide.

4. DUTHSat Components and Subsystems

Owing to its multi-national nature, a key aspect of the CubeSat initiative is that all critical components of the CubeSat are available as Commercial-off-the-shelf (COTS) components without export restrictions, contrary to most aerospace-qualified components. This significantly reduces costs, while the standardization of all subsystems has lead to greatly minimized integration efforts. However some COTS components that are commonly used by CubeSats in space have limited capabilities, such as low bit-resolution, high power consumption, and also are not radiation hardened: Space systems operate in conditions that involve plasmas and high-energy electrons, protons and heavier ions that are hazardous to the electronics of common technological systems, which are vulnerable to Single-Event Upsets (SEU), Single-Event Latchups (SEL) and Total Ionizing Doze (TID). The Space Research Laboratory of the Democritus University of Thrace (DUTH/SRL), with a long-term experience in the development of space ASICs components that are miniaturized, ultra-low-power, high-resolution and also radiation hardened, is demonstrating through DUTHSat solutions that can be used in any future CubeSat-based missions in more harsh environments than QB50, enhancing their capabilities and reliability, and also expanding the region in space where they can safely operate.

In the schematic of **Figure 1** we present an overview of the CubeSat design, including the power and data connections between different sub-systems. An overview of the design of the DUTHSat Subsystems and their relative positioning is shown in **Figure 2**. In further detail, the main DUTHSat subsystems include the following:

4.1 On-board Computer (OBC): The On Board Computer (OBC), the "brains" of DUTHSat, is responsible for all functions of the spacecraft, including deploying the antennas and mNLP booms, spacecraft telemetry data collection, attitude determination and control execution, constructing or deconstructing a file in order to upload or download it to the Ground Station, controlling the power in every subsystem, receiving and executing commands from the Ground Station, automated failure recovery, high-level system and payload control, etc. The OBC also monitors spacecraft temperature and housekeeping parameters, and plays a supervisor role for the power subsystem by interfacing with battery monitors and recording voltage and current levels of the batteries, automatically switching off non-critical subsystems in case of low levels of power. The OBC is interfaced with the Communications subsystem through which it receives ground station commands and transmits data and satellite status information. DUTHSat uses a CubeComputer OBC designed by Stellenbosch University, which is based on a high performance, low power 32-bit ARM Cortex-M3 based processor. Other features of the OBC include: PC104 bus connector, Flash Memory Data Storage, MicroSD card support, Power monitor/power-on reset, CAN bus interface, UART interface, SPI interface, GPIO pins, ADC interface and I^2C interface. Single Event Upset protection is implemented by means of an FPGA based flow-through EDAC, and Single Event Latchup protection is implemented by detecting and isolating latchup currents. For robustness, no operating system is used in the DUTHSat design. This decision creates several dif-

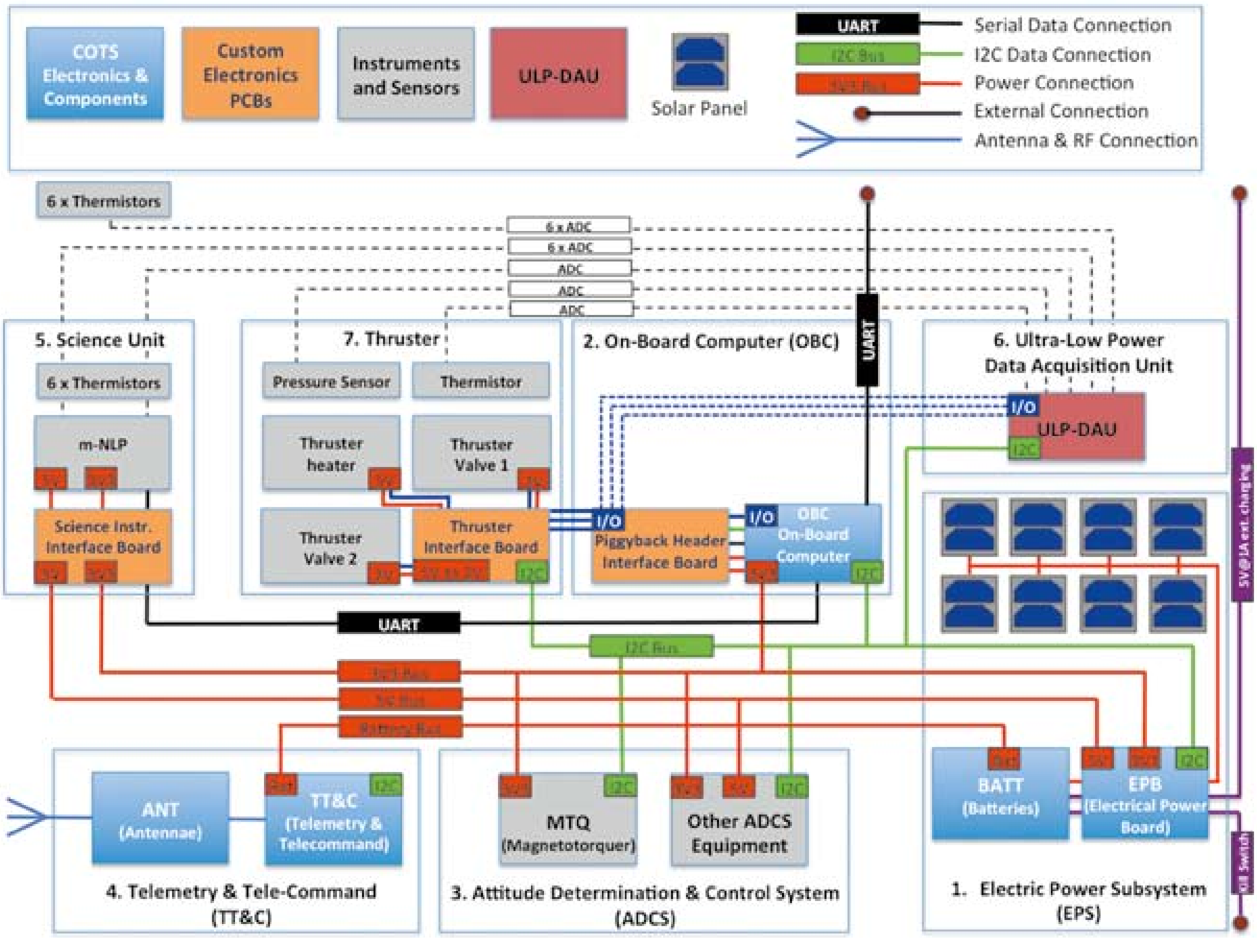


Figure 1: *Overview of the DUTHSat subsystems, including power and data connections between different sub-systems.*

ficulties in the design process, as all low level drivers (e.g. CAN,UART,SPI, GPIO, ADC,I2C) are created from scratch. Also, if an operating system is not used, techniques such as threading and schedulers that are used by default in every operating system cannot be used in the satellite. The advantages are that the code can be much more time and energy efficient, and that system engineering has much larger flexibility in the design of satellite operations.

4.2 Electrical Power Subsystem (EPS): The Electric Power Subsystem (EPS) includes high-efficiency solar panels placed at the sides of the CubeSat, a Power Distribution Module and Battery. Power is expected to be 4.6W at ambient temperature with a supply voltage of 3V3 and 5V. A Li-Ion battery of 2600mAh has been selected after extensive orbital and subsystem simulations. The power is supplied to all subsystems through the NanoPower P31U power supply designed by GOMSpace. The power capabilities of this power supply are for missions with power demands of up to 30W. The power coming from the solar panels and/or from the battery is used to feed the output power buses of 3.3V@5A and 5V@4A. Each of these buses has three individual output switches with over-current shutdown and latch-up protection. Finally, a heater is automatically switched on to protect the batteries from very low temperature and increase battery life.

4.3 Communications Subsystem: The Space Segment of the Communications Subsystem is formed from the antennas and the TRXVU VHF/UHF Transceiver, which enables the system to have full duplex capabilities with telemetry, telecommand and beacon capabilities on a single board. The peak power consumption of the transceiver is < 1.7W while it only uses <0.2W on receive only mode with an average transmit power of 22dBm. The transmitter frequency is controlled from the installed crystal and ranges between 400-450 MHz while the receiving frequency ranges between 130-160 MHz. DUTHSat's communication frequencies are 436.420 for downlink and 145.810 for uplink. The modulation scheme for downlink is RRC-BPSK (Root-Raised Cosine Binary Phase-Shift Keying). For uplink it will use the AFSK scheme on FM with 1200 b/s bit rate. The supported data rates from TRXVU are 1200 to 9600 bits per second with the protocol AX.25 for the communication channel. The antennas have a crossed UHF/VHF dipole configuration and deploy from inside an enclosure through a command from the OBC that is issued upon ejection of the satellite from its P-POD.

4.4 Attitude Determination and Control Subsystem (ADCS) and GPS: An Attitude Determination and Control Subsystem is used by DUTHSat, in order to achieve the following: a) Alignment of the long axis of the satellite with the velocity vector so that the

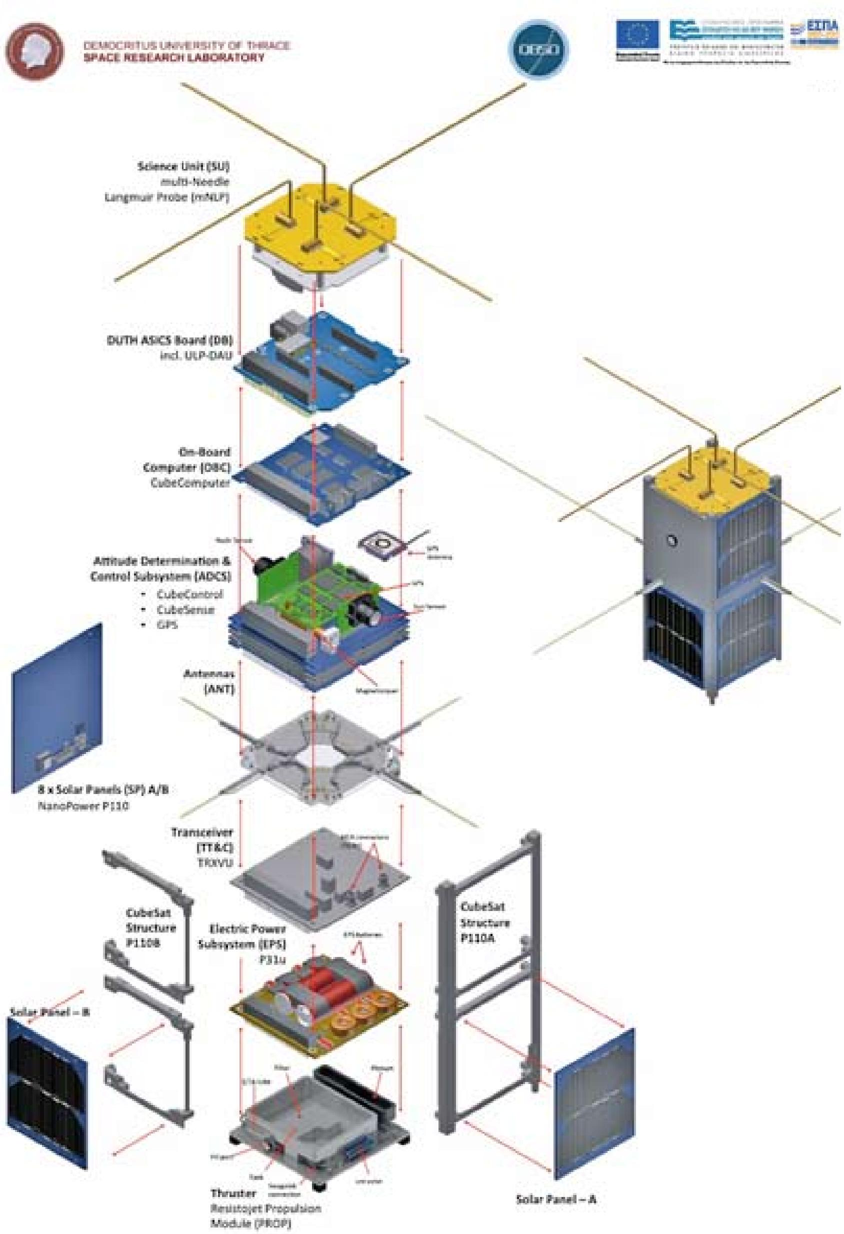


Figure 2: *CAD drawings of the subsystems of DUTHSat (left) and a drawing of the final, assembled satellite (right) with deployed antennas and Langmuir Probe booms.*

experiment package is pointed in the direction of motion (velocity-vector stabilization). b) Control of the attitude so that there is less than 5° between the long axis of the satellite and the velocity vector, down to 250 km altitude (velocity-vector pointing accuracy). c) Measurement of the satellite velocity-vector attitude to within ±1° at the time of receiving data from the payload (velocity-vector attitude knowledge). d) De-tumbling and stabilization during commissioning phase within 2 days. e) Recovery from tip-off rates of up to 100°/sec (tip-off rate recovery). An ADCS that is tailored to the above needs has been developed at the University of Surrey together with Stellenbosch University. This ADCS is modular and in its full configuration it can achieve 3-axis stabilized attitude control, accurate position, velocity & time from a GPS, <1° roll, pitch, yaw stability. The sensors that are used in the various modes of operation of the ADCS include a Y-axis aligned rate sensor, Magnetometer, Coarse Sun Sensors, Sun Sensor, Nadir Sensor. This configuration has relatively low power consumption (2W for 3-axis mode), compact size (0.4U), and low cost. DUTHSat will also feature a GPS receiver for timing and position determination purposes. The Novatel OEM615 GPS receiver module with special Space Firmware is used. The GPS receiver will also interface to the ADCS to assist the attitude determination process as well as in obtaining a timing stamp for the CubeSat.

4.5 Ground Station at DUTH: The Ground Station of DUTHSat is located at the laboratories of the Department of Electrical and Computer Engineering of the Democritus University of Thrace, at address: Vasilisis Sofias 1, 67100, Xanthi, at a Latitude of 41° 08'32.81" and a Longitude of 24° 53'24.83"**.** The equipment used in the ground station together with the setup and interconnections are given in the schematic of **Figure 3a**. The antennas and the indoor equipment of the ground station are shown in **Figure 3b** and **3c**.

4.6 Satellite bus, Structure and Thermal Subsystem: For the QB50 project a 2U CubeSat structure is baselined, which has an aluminum chassis with an outside envelope of 100 × 100 × 227.0 mm. The QB50 Science Unit will be accommodated at one end of the CubeSat structure, in the spacecraft ram velocity direction. The thermal control subsystem is particularly important in the QB50 mission: During the gradual re-entry large temperatures will develop, and eventually the CubeSat will ablate due to friction with the upper atmosphere. The operational range of the primary Science Unit is –20° to +40°, and, in order to extend measurements at as low altitudes as possible within the largely unknown lower layers of the Thermosphere, thermally conducting plates will be used in the design to serve as a passive heat dissipation and thermal control system: this will be done by attaching struts, plates and heat conducting wires, which in turn will be attached to a heat dissipation plate, at the lower end of the CubeSat (anti-ram direction).

4.7 Primary Payload: multi-Needle Langmuir Probe, Thermistors, Magnetometer. The main payload of DUTHSat is a multi-needle Langmuir probe system. Langmuir probes have been widely used to determine plasma electron density and temperature in space. The Langmuir probe works by placing an exposed conductor in a plasma, biasing it relative to a reference potential and measuring the collected current. A swept bias probe sweeps the bias voltage from a negative to a positive value, and the collected probe characteristic makes it possible to determine

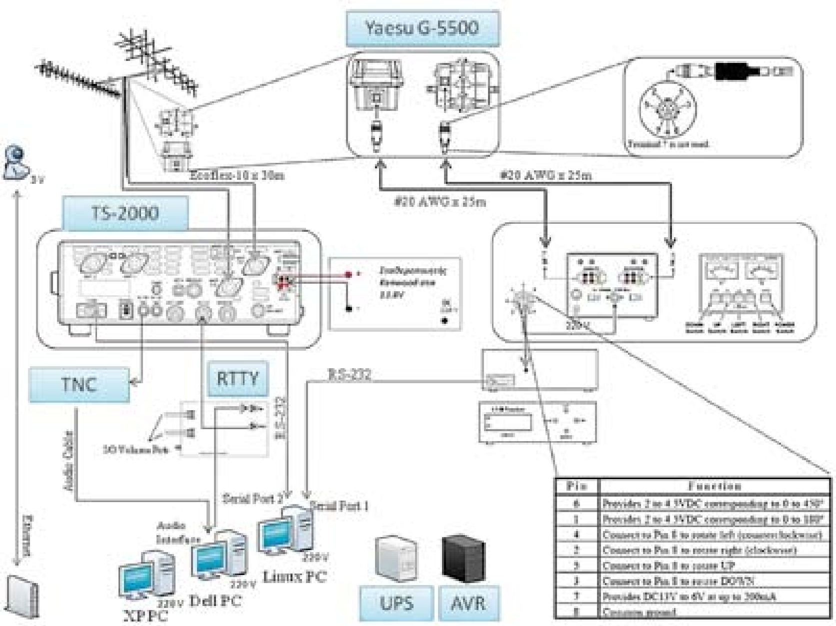


Figure 3: *a) Layout of the Ground Station equipment at DUTH; b) Antennas of the Ground Station and c) the indoor equipment at DUTH.*

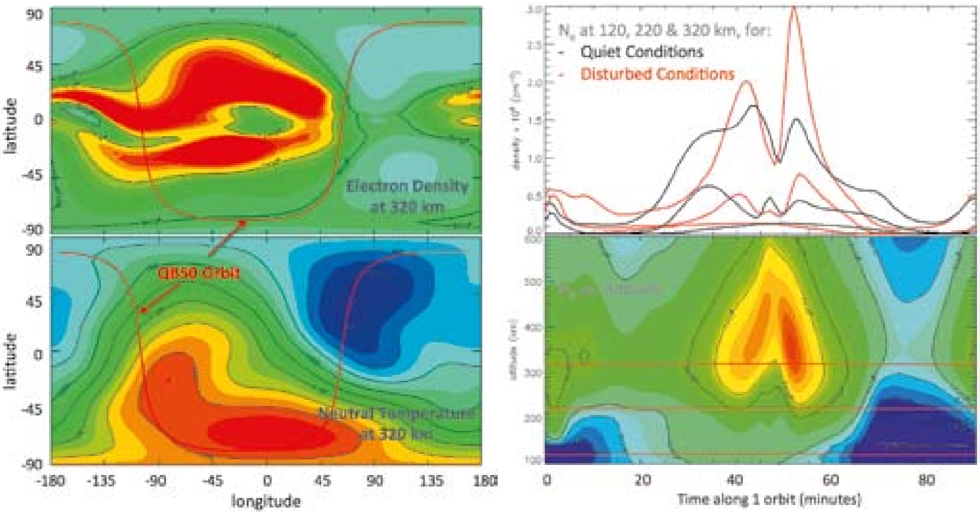
electron density n_e, electron temperature T_e and the spacecraft potential. In addition, Thermistors will be monitoring the Temperature at various locations on the spacecraft and a magnetometer will provide magnetic field measurements along the orbit.

4.8 Secondary Payload: DUTH ASICs Board and ULPDAQ chip. In addition to the mNLP Science Unit, DUTHSat will house an Ultra-Low Power Data Acquisition Unit, ULP-DAU, which is designed as a prototype smart-sensor data acquisition system-on-a-chip for use particularly in micro/nano/pico-satellite missions, but with features that will also be attractive to larger missions. This prototype will be flown in the DUTH/SRL developed nano-satellites of the CubeSat standard so as to demonstrate that the boards used currently by CubeSats can be replaced with ASICs, drastically reducing the size, weight and power requirements of the CubeSat avionics and I/O units. Thus, this mission also provides an opportunity to flight-test ASICs microchips developed at DUTH, which would accelerate their acceptance as standard and flight-proof components for other larger space missions; it is expected that the DUTH ASICs microchips will prove to be an invaluable asset in micro/nano/pico-satellite missions, where space, power and reliability are critical.

5. Science Questions and Educational Aspects of QB50

5.1 Motivation – Why Study the Upper Atmosphere? The Earth's upper atmosphere, which includes the Mesosphere and Lower Thermosphere, together with the Ionosphere (MLTI) is a complex dynamical system, sensitive to effects both from above and bellow. From above, the sun produces dramatic effects and significantly alters its energetics, dynamics and chemistry in a way that is not entirely understood; and from below, atmospheric motions are dominated by poorly understood gravity waves and tides that both propagate through and dissipate in this region. The response of the upper atmosphere to global warming in the lower atmosphere is also not well known: whereas the increase in CO_2 is expected to result in a global rise in temperature, model simulations predict that the thermosphere might actually show a cooling trend and a thermal shrinking of the upper atmosphere, and might play a role in energy balance processes. However, despite its significance, the MLTI region is the least measured and least understood of all atmospheric regions: Situated at altitudes from 50 to ~300 km the MLTI region is too high for balloon experiments and too low for orbital vehicles, due to significant atmospheric drag. Even with the new advances from remote-sensing measurements from missions at higher altitudes, this remains an under-sampled region with many remaining open questions. Thus it is not surprising that among scientists the MLTI region is often called (quite appropriately) the "Agnostosphere". The continuous and ever-increasing presence of mankind in space, and the importance of the behavior of this region to multiple issues related to aerospace technology, such as orbital calculations, vehicle re-entry, space debris lifetime etc., make its extensive study a pressing need. The QB50 mission targets to perform measurements in exactly this region, and, though instrumentation will be limited due to spacecraft size and power, the combination of the large number of in-situ measurements from all 50 CubeSats will be able to provide answers to some of the questions on the sequence of events that lead to MLTI heating and expansion, as well as its composition.

5.2 Upper Atmosphere Electrodynamics Modeling: DUTH/SRL has ex-



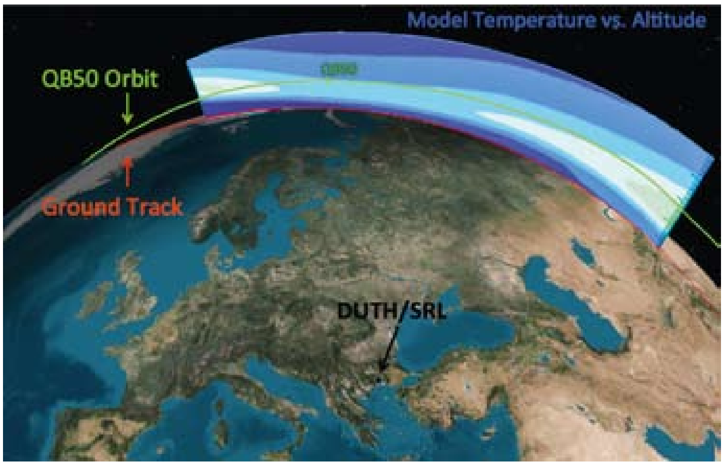


***Figure 4:** DUTHSat measurement simulations: a) Electron density (Ne) over one orbit at three altitudes, for quiet and disturbed conditions; b) Electron Density and Neutral Temperature vs. latitude and longitude and DUTHSat ground track; c) Model temperature vs. altitude at high latitudes together with a sample QB50 orbit. The location of the ground station at the Democritus University of Thrace is also shown.*

tensive expertise in modeling and data analysis in the Mesosphere-Lower Thermosphere-Ionosphere (MLTI); DUTH/SRL has undertaken and has recently successfully completed an ESA project titled "Electrodynamics Simulations in support to Future MLTI Missions", aiming to investigate the range of variability of key variables in the MLTI. Through this project a number of key MLTI models were run for a range of input conditions (solar, geomagnetic, seasonal) and the results from the models were intercompared and also compared against measurements. The models and corresponding variables investigated are listed below:

- **TIE-GCM**(**T_n**,T_i,T_e,U,W,**O**,**O_2**,NO, $N(^4S)$,$N(^2D)$,O^+,O_2^+,N_2^+,NO^+,N^+,N_e,G-Potential,E-Pot)
- **GUMICS-4** (N,P,U,T,MF,EF,$\Sigma_{Pedersen}$, Σ_{Hall}, E-Potential, PP power, Joule heating, FAC)
- **IRI-07** (**N_e**, T_e, T_i, **H^+**, **He^+**, NO^+, O^+, O_2^+, ion drifts, TEC, F1 and spread-F probability)
- **NRLMSISE-00** (T_n, He, **O**, **O_2**, **N_2**, Ar, H, N, Density, collision frequency)
- **CHAMP Currents Model** (Horizontal and Field Aligned Currents)
- **Alpha parameter Model** (Pedersen/Hall conductivity ratio)
- **HWM-07** (Zonal and Meridional winds)

In the list above we mark in **red** the MLTI variables that will be sampled by the QB50 CubeSats. The analysis performed at DUTH/SRL will allow for the optimal calibration of the QB50 Science Units and will play a key role in the data analysis, through comparisons of the measurements of all 50 QB50 sensors with current state-of-the-art models. Some examples of running QB50 orbits through the above models and sampling electron density and neutral temperature through the models are presented in **Figures 4a** and **4b**, as described. An overview of the DUTHSat orbit together with a cut-out of modeled temperatures as a function of Latitude, Longitude and Altitude is shown in **Figure 4c**.

5.3 Educational Aspects of the QB50 CubeSat Initiative: Together with its scientific impact, the QB50 initiative has an important educational aspect: the QB50 CubeSats are being designed and built by a large number of young engineers, supervised by experienced university staff and guided by the QB50 project through formal reviews and feedback. At the same time, space mission analysis and design procedures and standards are followed, introducing in the optimal way young engineers in a broad variety of aspects of space projects. These engineers will not only learn about space engineering in theory but will leave their universities with hands-on experience. At the Democritus University of Thrace, the design and construction of the satellite is accompanied by a series of classes on Space Systems, Space Applications and Space Electrodynamics; furthermore, multiple undergraduate and graduate diploma theses are focused on Satellite Subsystems. The students that participate in this project have a unique opportunity to follow all phases of a space mission, from design to spacecraft development, integration with instruments, testing, launch, tracking and finally to receiving and analyzing valuable scientific data.

6. Status, Schedule and Satellite Operations

Currently, DUTHSat is undergoing its "flat-sat" tests, which involves interconnecting all subsystems of the satellite "flat" on the laboratory bench, so that all functional tests can be conducted, before assembling and integrating the Flight Model with the CubeSat structure (**Figure 5**). After integration, the Flight Model will undergo a rigorous set of tests (functional, electrical, thermal, vacuum and vibration), to ensure that the satellite will be able to withstand the harsh space environment, including the intense vibrations during launch. These tests will be followed by pre-launch operations and final checkout tests, which will include a flight-like full-satellite testing; this will include testing satellite operations on internal batteries and solar arrays, with all beacons and devices on, testing communications with the Ground Station, telemetry and payload data collections, etc. After testing phase is completed, DUTHSat will be shipped to the QB50 coordinators and participating entities for integration with the CubeSat deployer that will release each satellite individually. The CubeSat deployer with all 50 satellites will then be shipped to the launch site for integration with the launcher. The early in-orbit operations and commissioning activities will include an Initialization Phase, in which the DUTHSat antenna is deployed, radio communication with the Ground Station at DUTH are established and the initialization commands are issued. Subsequently, during the Characterization and Commissioning Phase, DUTHSat functions and overall health will be monitored. This phase also includes achieving attitude stabilization and testing DUTHSat instruments. After achieving attitude stabilization, DUTHSat will move on to the Mission Phase, switching on the instruments in the appropriate mode and gradually maximizing the amount of science data downloaded and reducing the amount of housekeeping parameters.

Figure 4: Graduate students of the Department of Electrical and Computer Engineering of the Democritus University of Thrace are working on the assembly of DUTHSat in a Controlled Environment area of the Laboratory of Electromagnetism and Space Research.

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