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BILSAT: ADVANCING SMALLSAT CAPABILITIES

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ABSTRACT

Small spacecraft technologies and capabilities are evolving to the point where the BILSAT 120kg spacecraft will this year demonstrate capabilities and performance similar to the 320kg UoSAT-12 mission launched in 1999.

Over the past few years, the design of small satellites has evolved from simple curiosities to effective, high performance systems, capable of competing with much bigger and much more expensive spacecraft. Within the framework of an agreement between SSTL and TUBITAK-BILTEN (The Information Technologies and Electronics Research Institute), a non-profit government laboratory located in Ankara, Turkey, a Technology Transfer Program was started in August 2001. This program includes the design, manufacture and launch of one Enhanced SSTL microsatellite platform, one engineering model for use in Turkey and the training of engineers in all aspects of the spacecraft design. Detailed design began using the Enhanced SSTL microsatellite platform as the starting point. The end product that will be launched in the summer of 2003, is the most advanced spacecraft ever designed by SSTL, carrying two advanced payloads developed by TUBITAK-BILTEN.

The spacecraft is a highly optimised satellite, with a mass of 120kg and including 14 cameras (in several imager arrangements), a 10m/s class resistojet propulsion system, VHF/UHF and S-band RF systems, tried and tested OBDH units in parallel with newly designed mass data storage and processing units, all this topped by a high performance AODCS subsystem, including two star trackers, GPS receiver (for both orbit and attitude determination), rate gyros, four momentum/reaction wheels, and what will be the first operational use of Control Momentum Gyros on a small spacecraft, to perform high agility manoeuvres. These units will be used to achieve the missions specified for this project, mainly full imaging of Turkey, stereoscopic imaging of selected targets, a Digital Elevation Map of Turkey, and communications. The present paper discusses briefly the technical characteristics of the spacecraft, but focuses on the mission aspects and how the different subsystems (namely the new subsystems and payloads) will be used to accomplish the mission. The operational modes of the spacecraft are discussed and the interaction of the AODCS subsystem with the OBDH and Imaging system is described in detail.

1 PROGRAMME OVERVIEW

The BILSAT-1 microsatellite is scheduled for launch on the 28th of July 2003, into a 686km 10:30AM-10:30PM sun synchronous low Earth orbit, on a Cosmos rocket from Plesetsk in Russia procured by SSTL for the satellites in the Disaster Monitoring Constellation (DMC). This will give BILSAT-1 an average orbit period of about 97.7 minutes. This orbit will give the Turkish ground station and the satellite a contact time of about 10 minutes per pass, with an average of four passes per day.

The main mission of BILSAT-1 is remote sensing, comprising two main cameras for this effect, supported by a customer developed experimental payload (COBAN). The primary multispectral imager of the satellite has a 26-metre ground sampling distance (at 686km altitude) with a swath width of 55 km and the panchromatic imager of the satellite with 12-metre ground sampling distance gives a 25 km swath width. The satellite has an off-pointing capability, provided by the ADCS systems, which (amongst other benefits) reduces the revisit time for any given point on the Earth. This off-track pointing capability is illustrated in

Figure 1. The revisit periods of the satellite for the multispectral imager with and without steering are 4 and 52 days respectively – and for the panchromatic camera are 5 and 116 days respectively.

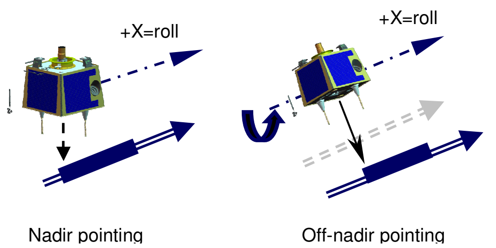

Figure 1: Slewing about roll axis makes off nadir pointing possible to improve revisit period.

Since the satellite can also be steered about pitch axis, it is possible to take images of a target on track from different angles, which will give BILSAT-1 a stereoscopic imaging capability. Using this feature of the satellite, it is planned to make a DEM (digital elevation map) of Turkey. To fulfil this mission objective, it is aimed to take as many pictures of Turkey as possible during the first five years of the BILSAT-1 mission. Apart from constructing a DEM of Turkey, the pictures taken from the satellite will be a very valuable resource for study in various areas like disaster monitoring, monitoring the urban areas around big cities in Turkey, and vegetation, for example.

BILSAT will also accommodate a store and forward type communications payload. This payload will be used by various organisations in Turkey to create public awareness of satellite technologies.

As a part of the know how training and transfer (KHTT) programme, additional payloads have been included on the satellite. Among these additional payloads, a multi spectral camera (the already mentioned COBAN) and a real time JPEG2000 image compression DSP card (GEZGIN) were developed by Turkish engineers, with the support of SSTL staff, to be accommodated on the satellite.

2 PLATFORM

BILSAT-1 (previously known as BILTENSAT-1) is a small satellite based on the enhanced micro satellite platform of SSTL. This is an evolution of the highly successful SSTL microsatellite platform, with improved specifications. The main improvements are a higher mass (around 120kg instead of 60kg), three axis controlled platform (with agile manoeuvring capability), medium resolution pan-chromatic and multispectral imagers, a more capable On-Board Data Handling (OBDH) subsystem and a high speed RF link operating at 2Mbps.

The main objective of the mission is remote sensing, and as such, the system has been designed around this requirement, with a set of subsystems that make the maximum use of the imaging capability installed on-board. The spacecraft will use star cameras and reaction wheels to control the satellite in three axis mode with an attitude control accuracy of ± 0.02 deg and with an attitude knowledge of ±0.006 deg. To achieve this very demanding attitude control, the spacecraft will also use its SGR-20 GPS receiver to determine its orbital position to within ±50m. To store the images generated by the imaging subsystem (and other payload data), the spacecraft is equipped with a set of solid-state data recorders, linked to the RF communications and imaging systems by high speed data links. These will be used for storage but also for in-flight processing of the stored data. A simplified block diagram of the satellite can be seen in Figure 2:

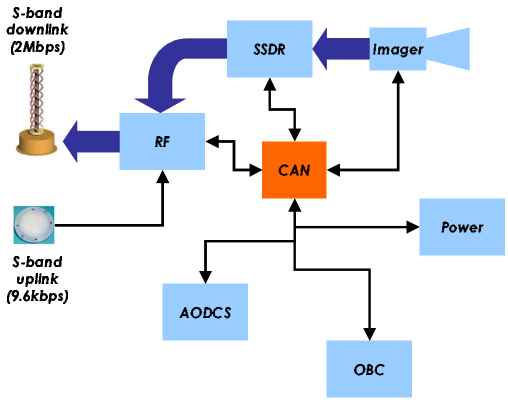

Figure 2 - Simplified block diagram of Bilsat-1

The spacecraft follows the standard SSTL approach of low cost design and, in line with this approach, extensive use of COTS components is made in the subsystems, while the overall system is designed to be highly resilient to non-nominal situations by implementing either full dual string redundancy (for mission critical subsystems), or by adopting a graceful degradation strategy (for non mission critical subsystems such as payloads). This approach allows a high degree of survivability of the mission without a prohibitively high cost.

The low cost approach also applies to the operations concept, which minimises the ground segment costs by reducing the personnel requirements through high levels of on-board autonomy. For this strategy to be viable, the satellite is designed to survive long periods without ground operator access or intervention.

3 AODCS SYSTEMS

The attitude determination and control subsystem of BILSAT-1 features a suite of sensors comprising four sun sensors, four rate sensors, two magnetometers and two star cameras (a GPS receiver is used for position determination). Four reaction wheels, three torque rods, and a gravity gradient boom account for the actuators. A block diagram of this system is shown in Figure 3.

The subsystem exploits the aforementioned actuators and sensors to provide the satellite with high accuracy full three-axis control for at least the first five years of its mission lifetime. During this full three-axis control mode, a control accuracy of ±0.02 degrees will be the target, along with attitude knowledge of ± 0.006 degrees.

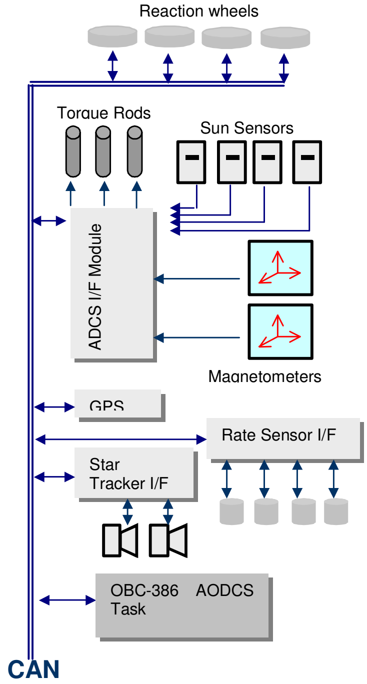

Figure 3: AODCS Block Diagram of BILSAT-1

The reaction wheels of BILSAT-1 are arranged in a tetrahedral formation, with one of the wheels being mounted in line with the pitch axis. All four wheels are accomodated on the space facing facet of the satellite. The wheels will run with a momentum bias, but the overall momentum of the system will be zero which means that the satellite will operate with zero momentum bias.

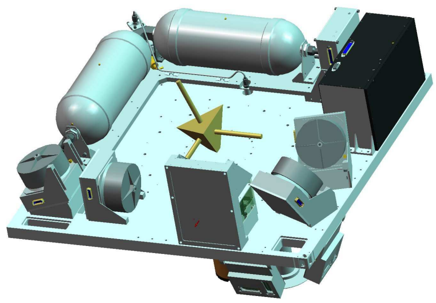

Figure 4: Four wheels are accommodated on the space facing facet in a tetrahedral configuration

Each wheel is capable of delivering a torque around 6-7 mNm in air. In vacuum (i.e. space) this figure goes up to 10 mNm. Thanks to the tetrahedral configuration, the wheel assembly is capable to deliver the satellite (about Y body axis only) twice as much of the maximum torque that a single wheel can supply. (i.e. a maximum of 20 mNm of torque is available about satellite Y body axis).

Wheels make it possible to control the satellite in a mode called “three-axis control mode” which will give the satellite the ability to slew about any defined axis. By means of this feature it is possible to achieve one of the mission goals that is to slew the satellite by up to +/- 30 degrees around the pitch axis to take pictures of a defined location on earth from different angles. This is illustrated in Figure 5

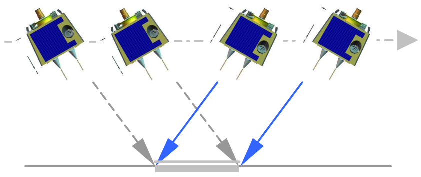

Figure 5: Illustration of 30 degree slewing about pitch axis to take stereoscopic images of a defined strip on the ground.

Slewing about a defined axis also makes it possible to align the thrust vector along a defined axis making it possible to do firings to correct for semi major axis of the satellite.

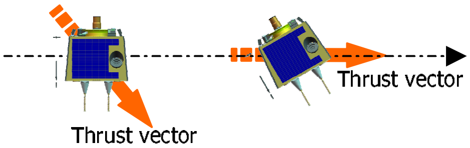

Figure 6: Three axis control mode makes it possible to align the thrust vector along the direction of the velocity vector

This feature of the satellite (slewing about any defined axis) will also make it possible to slew the payload to take off-track images (payload slewing and track a defined target on the ground (target tracking).

The reaction wheels on board the satellite are expected to operate for a minimum of five years before reaching their expected lifetime limits. After this time the gravity-gradient boom will be deployed and the satellite will enter an extended mission mode. Obviously, in this second phase, the satellite will no longer be controlled in full three-axis mode and, during this extended life time period, the satellite will perform a nadir pointing mission with +/- 0.3 degrees pointing accuracy. Because it is not three axes controlled any more, it will lose its capabilities of three-axis control mode like off-track imaging, stereoscopic imaging, thrust vector alignment; however it will still be possible to take images in the nadir pointing direction.

Torque rods are used during nominal operations phase to dump the excess momentum accumulated on the wheels and also as the main actuator during LEOP. During the nominal operations phase, external disturbances are absorbed by the wheels thus increasing their momentum. The momentum on the wheels will reach a limit at which their angular velocity can no longer be increased; before this point is reached, magnetic torquers supply external torques to bring the angular velocity of the wheels back to nominal operating values.

Figure 7: The propulsion system installed on the satellite to perform semi major axis corrections

BILSAT also has a propulsion system that gives the satellite the opportunity to perform some orbital manoeuvres. These manoeuvres allow the satellite to alter its semi major axis and thus the eccentricity of the orbit.

A single thruster fires through the Centre of Gravity to perform orbit change manoeuvres.

The propulsion system uses "butane" as the propellant. The system dry mass is less than 6 kg and the propellant mass is around 2.3 kg. It is capable of supplying a thrust of around 50 mN which delivers the satellite a delta V of around 10 m/s. The use of a heater in the thruster will increase the efficiency of the propulsion system as seen in the AlSAT-1 satellite. In this case, the expected delta V will increase by up to 50%.

The spacecraft is equipped with two SSTL Altair HB star cameras, the last evolution of the SSTL star cameras. These provide the AODCS software with processed attitude information, that can be used to compute the attitude to within the requirements of the mission. Each camera includes its own processing unit, based on a StrongARM processor and is thus a standalone unit (see Figure 8). The total weight of one camera is 1.7kg, including the carbon fibre baffle and the mounting bracket and requires a total power of 2.8W, making it a very attractive solution for a small satellite like BILSAT-1

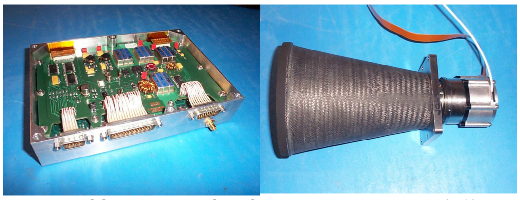

Figure 8 - SSTL Altair HB Star Camera: Processing unit (left) and Camera Head (right). Units not shown in same scale

The performance of the star cameras when operated together with the other elements of the AODCS has been object of extensive simulations, namely to establish the worst case scenarios. Figure 9 presents the results of such a simulation, where only three visible stars were used to get the attitude vector. If ten stars were considered, the values would be half of the ones seen in the graphic.

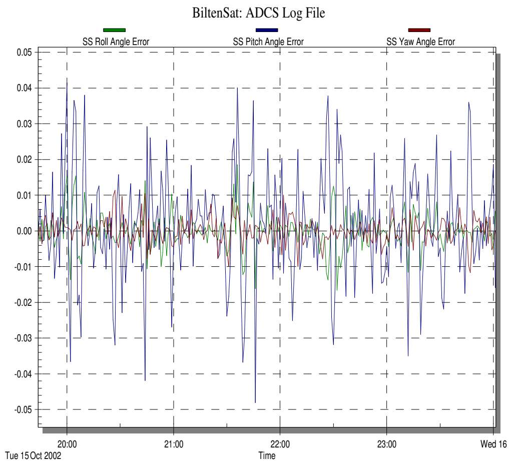

Figure 9: Worst case (using only 3 stars) simulation of maximum expected errors for orbit determination (vertical scale is in degrees)

To complement the star cameras, namely during fast attitude manoeuvres, four MEMS gyros are employed as rate sensors. Three of these gyros are aligned along each axis, and one of them is aligned in a skewed manner so that it can provide rate information about three axis.

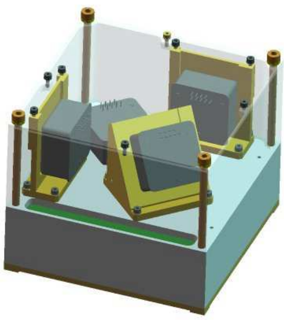

Figure 10: Four MEMS gyros are used to measure the rates

Although the Star tracker is the most precise attitude sensor on the satellite, it fails to provide rate information when the slew rate is above 0.5 deg/sec. In such cases, rate gyros are primary sources of reference for rate information. Because of this reason, the gyro assembly on BILSAT is particularly important during stereoscopic imaging manoeuvres.

The GPS receiver on the satellite is a SSTL-built system which can supply a position knowledge of +/- 50 m. The four GPS antennas integrated on the space facing facet of the satellite, makes it possible to determine the attitude up to +/- 1 degree.

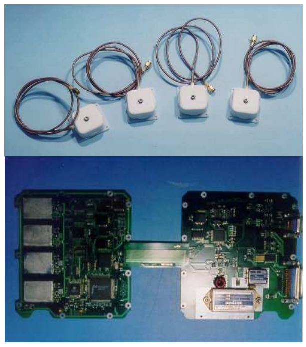

Figure 11: The SSTL SGR-20 GPS receiver is capable of determination of attitude as well as position information

4 POWER SYSTEM

Power generation is achieved by body-mounted solar panels with single junction ENE GaAs cells. The solar panels were assembled at SSTL's premises and each panel is capable of providing 58 Watts @ 28°C at the beginning of life. Each panel feeds a dedicated Battery Charge Regulator (BCR), operating with maximum power point tracking or battery end of charge modes.

The satellite has a single battery pack consisting of 22 4Ah NiCd cells, providing an unregulated 28V main power bus to the subsystems. A regulated 5V bus is provided. The power distribution is achieved by means of fused lines for essential bus systems, and the payload and subsystem operations are controlled by commanding the electronic power switches on PDM (Power Distribution Module).

Payload operations are scheduled in order to keep the battery depth of discharge (DoD) at the design level of 15%, although analyses show that the DoD could reach 20% for some particular orbits where intensive operations are required.

5 ON BOARD DATA HANDLING

The On-Board Data Handling subsystem consists of three main components: On-Board Computers (OBC), Solid State Data Recorders (SSDRs) and the data network (general data and telemetry).

The satellite features one Intel 80186 based OBC (16 MB of memory) and two Intel 80386 based OBC (32 MB of memory each). These are the standard SSTL OBC186 and OBC386 units, extensively tried and tested on previous SSTL led missions. For storing large amounts of data on board, two solid state data recorders (SSDRs) are available. One of these SSDRs is based on the StrongARM (SA1100) processor and has 128 MB of memory and the other is based on a Power PC processor and has 512 MB of memory. Both these units have the capability for processing the stored data, allowing data compression or selection of data on-board.

To connect the different subsystems of the spacecraft, four main solutions have been adopted:

- Point-to-point customised links
- Point-to-point low speed TTL links
- Point-to-point high speed LVDS links
- Dual redundant CAN network

The main telemetry and telecommand link is the CAN network, currently in use in several missions, including the UoSAT-12 minisatellite mission. Point-to-point connections are required for back-up access (in case the CAN develops a fault) or for systems that require data rates and/or have timing restrictions not compatible with the use of the CAN network.

6 RF COMMUNICATIONS SYSTEM

The communication system of Bilsat-1 is a hybrid system, featuring a UHF/VHF system and an S-band system. The UHF/VHF subsystem has been selected because of its very long heritage on SSTL missions. During the nominal mission, it will act as the backup communications system, but it is intended to be used as the prime system during the commissioning phase. The S-band system will be used during the nominal mission phase as the communications system, for both data and TT&C communications.

The VHF receivers employ CP-FSK modulation, with an upload data rate of 9.6kbps. There are two units operating in a hot redundant mode. Four blade antennas provide omnidirectional coverage. The UHF transmitter has two amplifier chains, to provide download rates of 9.6kbps, 38.4kbps and 76.8kbps using a set of four blade antennas that provide omnidirectional coverage.

The S-band system comprises two 9.6kbps, CP-FSK receivers, and two 2Mbps, BPSK transmitters. This is the main communication system under nominal conditions, but given its relative directionality, it is not suited as a backup/emergency system.

7 STRUCTURE

BILSAT-1 is a challenging satellite in that has similar (and in some cases superior) capabilities to the minisatellite UoSAT-12, in a smaller and three times lighter platform. The accommodation of the subsystems was always going to require a careful exercise of structural design. But in addition to accommodation, there are also thermal and pointing accuracy requirements, which impose constraints on the structure.

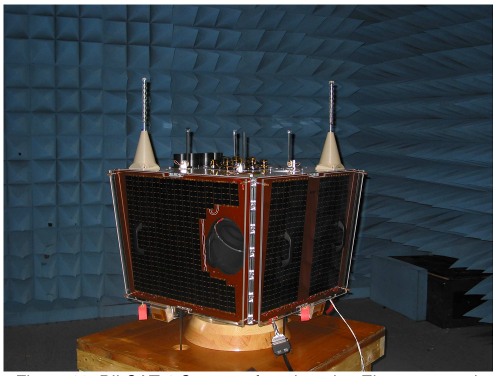

Figure 12: BILSAT-1 Spacecraft undergoing Electromagnetic Compatibility tests in April 2003

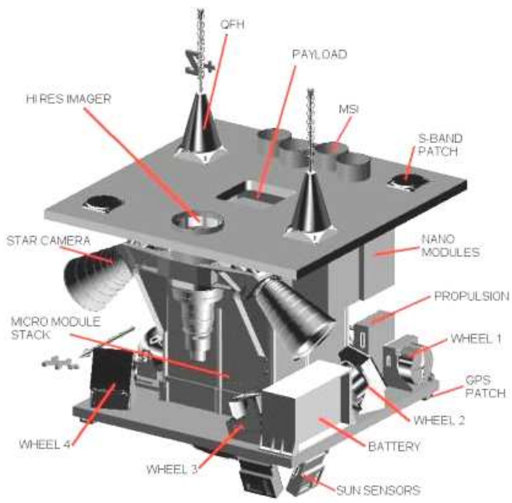

Figure 13: Annotated Interior View of BILSAT-1 Spacecraft

Figure 12 is an image of the satellite while at EMC testing while Figure 13 illustrates the structural design of the satellite. The core structure comprises the standard SSTL self-supporting stack of equipment boxes. Each modulebox carries one or more subsystems, serving as both subsystem enclosure and structural element. On top of the stack, below the Earth Facing Facet, there is an enclosure that holds some of the customer built payloads. This is surrounded by shear panels, which connect and transfer the loads from the stack to the facet, and to which, non-structural "mini-stacks" of "nanotrays" are bolted. These nanotrays represent the next step in miniaturisation, and are a direct result of the work done by SSTL on developing, smaller, more efficient subsystems, demonstrated on the SNAP-1 nanosatellite. The imagers are also attached to these shear panels, mainly for thermal reasons, since the inner core of the spacecraft is thermally very stable, showing little thermal cycling during both one orbit and during the orbital seasons. The star cameras and the pan-chromatic imager are mounted on the same assembly, a thermally stable platform. This ensures that the attitude knowledge when imaging is optimal.

In order to increase the power generation capability, the body mounted solar panels were canted by 5º, optimising their illumination for the selected orbit. They are thermally coupled to each other, creating an external shroud that takes most of the varying thermal loads, reducing the thermal stresses on the interior of the satellite.

8 EARTH IMAGING SYSTEM

Although strictly speaking the Earth Imaging System is a payload, it is also true that it is a fundamental platform subsystem in a mission that has as main objective remote sensing. Two imagers are included on Bilsat-1:

- Pan-chromatic imager
- Multispectral imager

The multispectral imager is composed of four individual cameras, each one operating in a different spectral band (red, blue, green, near infrared) with a ground sampling distance of 26m.

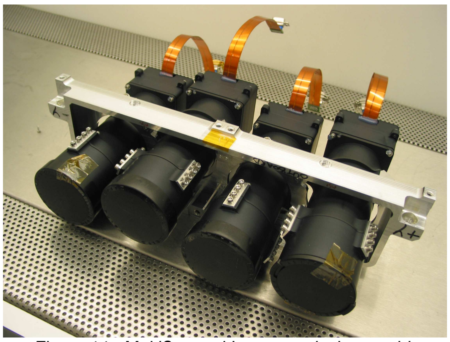

Figure 14 - MultiSpectral Imager optical assembly

The panchromatic camera has a ground sampling distance of 12 m and is designed around a COTS 400mm lens.

The imagers use the Kodak® KAI-4000 array sensor, and include image memory used to store images prior to transfer to the mass storage devices.

Special care has been taken in ensuring the thermal stability of the pan-chromatic camera to reduce perturbations of the image due to temperature induced misalignments. A detailed study of the problem was performed by SSTL, and its results were inputted into the design.

9 CONTROL MOMENT GYRO

BILSAT-1 includes a 2-Control Moment Gyro (CMG) cluster for agile pitch-axis control, that are an experimental payload. These units are the result of the extensive experimental work performed by the Surrey Space Centre in this field. CMGs have not been used before on small or commercial satellites. Reference [2] details an analysis on the applicability of CMGs on small satellites. The units will operate as a complement to the standard AODCS subsystem, either replacing the wheels or aiding the system in high speed attitude manoeuvres. SSTL is testing the CMGs as a future alternative to momentum/reaction wheels as they are expected to offer a more efficient and faster manoeuvring capability. For instance, the CMG used on BILSAT-1 will allow a slew of 40º in around 20s.

CMGs are unique in that they can provide unique capabilities to satellites mainly due to their high torque and angular momentum capabilities. Drawbacks on the use of CMGs are mechanical complexity, reliability and high cost. However, new technologies based on COTS and novel research has indicated that it is possible to design affordable CMGs for agile platforms [2].

The CMGs designed for BILSAT-1 are based on COTS motors and employ a DC Brushless Motor (BDCM) to rotate the flywheel and a Stepper Motor (SM) that gimbals the flywheel assembly in order to provide gyroscopic torque. The twin CMG payload can be also operated in momentum and reaction wheel modes as well as Variable Speed CMGs (VSCMG).

The CMGs are placed in a 2-CMG parallel arrangement where the gimbal axes are perpendicular to the x-y plane and are parallel to each other (Figure 2).

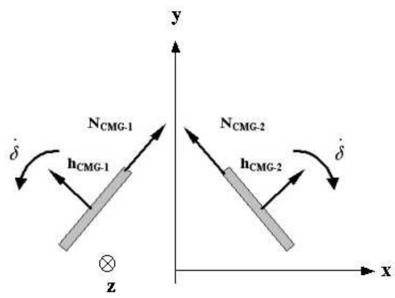

Figure 15: CMG arrangement

The CMGs have been designed using SSTL's architecture. It communicates via a CAN bus and each CMG has its own electronics board in its module. The characteristics of the CMG are presented in Table 1.

DIMENSION	135 x 155 x 190 mm
Mass	2.2 kg
Power (Max.)	12W
Torque	95 mNm
Angular Momentum	0.28 Nms
Gimbal Rate	9°/s

Table 1: CMG Characteristics

The main design requirement for designing the BILSAT-1 CMG experimental payload is the 2°/s average slew pitch rate capability. Thus the characteristics of the CMG have been derived from this requirement. Simulations have indicated that this is accomplished as expected. For the BILSAT satellite (Table 2) a 40º manoeuvre in 20 seconds is used an example to demonstrate the 2º/s average slew rate requirement. The manoeuvre is completed in 20s and rotates the spacecraft by 40.6° about the pitch axis. A torque of 88.7 mNm is used to complete the manoeuvre.

Satellite Inertia **[I_x, I_y, I_z] (kg-m^2)**	[10, 10, 10]
Mass (kg)	130
Average Slew rate (º/s)	2

Table 2: Simulation Parameters

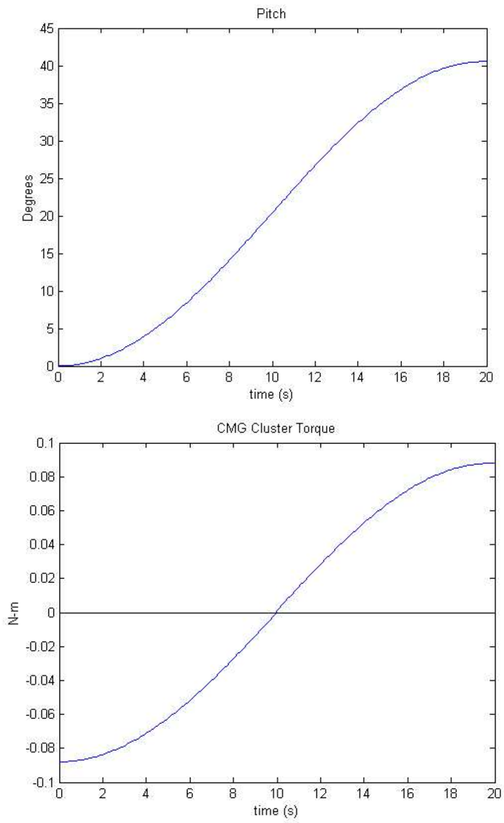

Figure 16: a) Pitch b)CMG Torque diagrams

At the date when this paper was written all CMG tests have been concluded and final tests are being made on the BILSAT-1 spacecraft. It is envisaged, after a successful launch, the CMGs will be commissioned and experimental campaigns will follow to demonstrate the capability of the CMGs.

10 CUSTOMER DEVELOPED PAYLOADS

In order to make maximum use of this technology transfer programme, volume, power and mass budget were reserved on the satellite design so that additional payloads would be developed and flown by various individuals/teams in Turkey. The main purpose of this was to incorporate various organisations in Turkey that could play a role in the production of subsystems and payloads for the space industry in the project and in the future. As a result of this decision, an additional multi spectral camera (COBAN) and a DSP card

(GEZGIN[1]) for real time image compression were developed at TUBITAK-BILTEN by Turkish engineers and researchers.

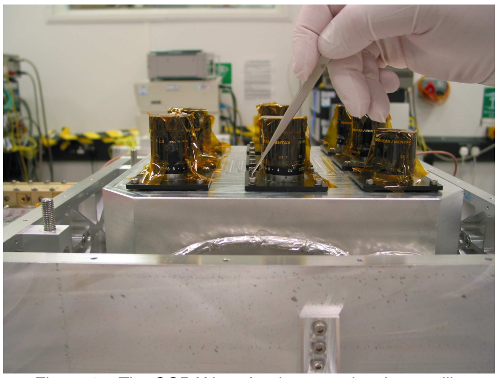

Figure 17: The COBAN payload mounted to the satellite

By developing additional payloads like COBAN and GEZGIN, BILTEN engineers gained expertise and experience on how to design and build systems for the space environments. Furthermore, both payloads will provide valuable information and help the platform to achieve its mission. Both units are fully integrated with the other subsystems of the spacecraft.

11 GROUND SEGMENT AND OPERATIONS

The operations concept of Bilsat-1 follows the same strategy used on previous SSTL missions: small infrastructure and low operational costs. This approach is currently used on other SSTL led missions, with good results.

The satellite has embedded autonomy in its design, requiring only minimum maintenance under nominal operations. In case of malfunction of the satellite, BILSAT-1 will revert to a safe mode, similar to the one in which the satellite is after launcher separation. This safe mode can be maintained for several days before any action must be taken on the ground (payloads will not operate in safe mode and so a fast recovery is desirable). In this way, the control groundstation does not need to be manned 24 hours per day, reducing the staffing level required. For BILSAT-1, the operators will only be on duty in the groundstation during routine maintenance of the satellite or when they are alerted that there is a problem with the satellite. The SSTL groundstation automatically alerts the operators via their mobile phones if there is a problem noticed during a ground pass of the satellite.

[1] See Ref. 1

BILSAT-1 will have only the most basic software installed on-board at launch. This is mainly intended to control the basic functions of the satellite until the flight software is uploaded to the different subsystems. This has the advantage of easy error correction of bugs in the software, easy upgrade of the software and allows changes to it to optimise the satellite's performance.

BILSAT-1 is controlled from a ground station in Ankara, built by SSTL. This ground station can support both VHF/UHF and S-band communications and is equiped with all the necessary control and storage devices. It is designed to operate automatically without the presence of an operator.

12 CONCLUSION

The BILSAT-1 Mission and spacecraft represent one of the most challenging and complex projects that SSTL has ever undertaken. Along with the other equally important aspects of the project, such as the facilities and KHTT program, the outcome is an extremely agile and capable spacecraft, which is able to carry out in-orbit operations of a nature not before seen in this class of satellite. The addition of two Research and Development Payloads designed and built entirely by BILTEN team engineers adds to the capabilities of this unique spacecraft.

13 REFERENCES

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