Redundancy Modeling for the X-Sat Microsatellite System

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SUMMARY & CONCLUSIONS

X-Sat, the first microsatellite indigenously developed in Singapore, was launched in April 2011. Following a series of checkouts, the satellite was declared operational mid Jun 2011. From then on, X-Sat was expected to go on operating for up to three years, totally unattended in the vacuum and temperature extremes of the space environment. Its isolation in space imposed a high reliability requirement for X-Sat. Redundancy to deal with single-point-failure was implemented throughout the X-Sat microsatellite system, whether it was hot, cold or k/n redundancies. If redundancy was not possible at the subsystem or unit level, then some form of redundancy was implemented at the component or parts level.

This paper discusses the modeling of the various redundancy schemes onboard the X-Sat Microsatellite to verify that these are adequate for the satellite to achieve its three-year mission life.

1 X-SAT MICROSATELLITE SPECIFICATIONS

The X-Sat Microsatellite was inserted by the Indian launcher PSLV (Polar Satellite Launch Vehicle) into a Sun synchronous orbit which means the satellite passes through the same spot at about the same time every day. At an altitude of 822km, it orbits the earth 14 times per day of which twice it comes within communication range with the ground stations at the Nanyang Technological University (NTU) or the Centre for Remote Imaging, Sensing and Processing (CRISP) at the National University of Singapore (NUS).

This microsatellite carries the an imaging payload IRIS which the project acquired from Satreci for environmental monitoring in the South East Asia Region such as forest fires, mud slides, and floods [1]. Images taken by the camera have a Ground Sample Distance (GSD) of 12 m (equivalent to 1 pixel on the image taken) and swath width of 50 km (i.e. the span of the image) at the reference altitude of 822km (see *Table 1* & *Figure 1*).

To conform to launcher requirements, the satellite dimensions were kept within 0.6 x 0.6 x 0.8m^3. The total mass of the satellite was 107kg, less than the launcher imposed limit of 120 kg.

Table 1: Specifications for the X-Sat Microsatellite

Orbit	Sun-synchronous
Altitude	822km
Payloads	Electro-Optical unit (IRIS) Parallel Processing Unit (PPU)
GSD	12m @822km altitude
Swath	>50km @ 822km altitude
Mass	106.68kg
Size	0.6m × 0.6m × 0.8m
Attitude Control	3-axis with 0.33^{o} (roll & pitch) & 1^{o} (yaw)
Solar Panels	2 deployable & 1 fixed (247Watts at EOF)
Battery	Li-Ion (13.5A-Hrs)
Telemetry Tracking & Command	S-Band (Consultative Committee for Space Data Systems or CCSDS)
Downlink	X-Band

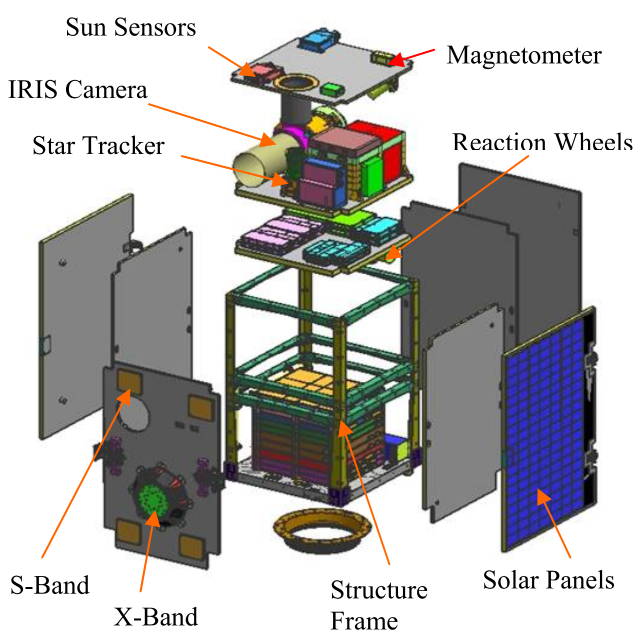


Figure 1: X-Sat Microsatellite Configuration

2 RELIABILITY REQUIREMENT FOR X-SAT

The high reliability requirement for a satellite such as X-Sat is due to its isolation in space. In orbit, it has to be lined up to the Earth so that the "talking-listening" face is always pointing at the Ground Station. It has to generate its own electrical power to keep itself in order and to operate the communications equipment on board.

X-Sat has to go on operating faultlessly for up to three years, totally unattended in the vacuum and temperature extremes of the space environment. It has to maintain the right internal temperatures although on the side facing the Sun, its surface may heat up to +90^{o}C while on the opposite side, the surface encounters a temperature as low as -60^{o}C.

Mechanical degradation is a lesser concern. During launch, the satellite withstood the vibration environments. Critical mechanical functions such as solar panel deployment were checked early in the mission.

Radiation from the sun degrades the solar arrays and thermal coatings. This decrease in cell efficiency was accounted for when sizing the solar arrays so that it should not have unforeseen effects on the satellite operational life.

Single event upsets disrupt IC operations, resulting in random failures [2]. These were minimized through hardware and software methods that allow autonomous recovery [3].

This high reliability requirement leads to the most exacting electronic and mechanical design, stringent selection of materials and components and high standard of manufacture. Any failure may require complex reconfigurations for rapid recovery.

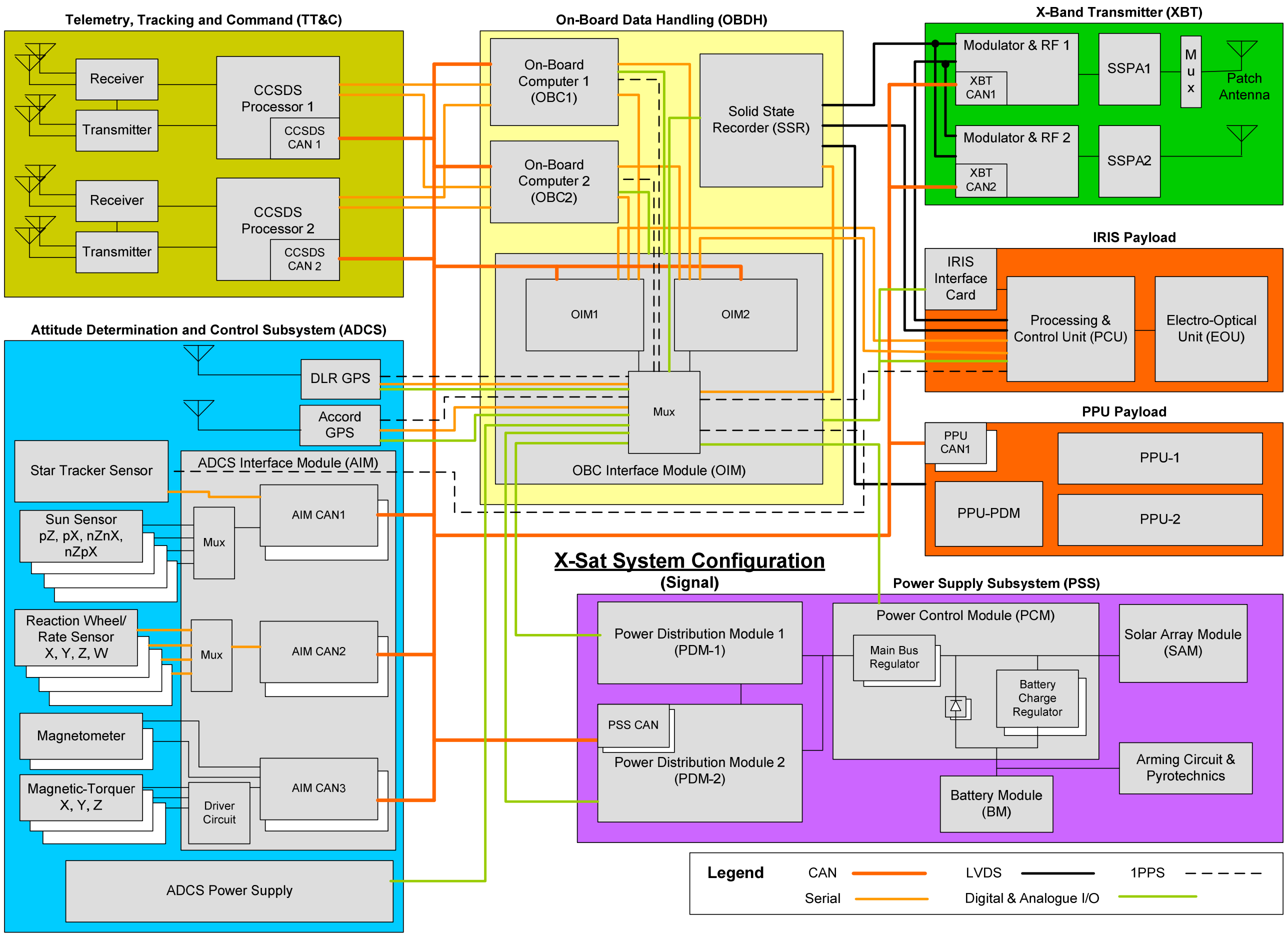


Figure 2: Functional Block Diagram of the X-Sat Microsatellite

3 X-SAT RELIABILITY BLOCK DIAGRAM

Reliability is of paramount importance to the X-Sat satellite and yet maintenance is impossible. Any single point failure that could cause catastrophic satellite failure must be addressed via redundancy. In other words, the satellite must carry its own pool of spares (see *Figure 1*, *Figure 2* & *Figure 3*). For example, the On-Board Computer (OBC) which processes and distributes commands as well as formats and stores data is made up of dual cold redundant OBC [4]. The Altitude Determination and Control Subsystem (ADCS), which tells the satellite where to point, is made up of a suite of redundant sensors and actuators, whether it is the sun sensors, reaction wheels or magnetic torque [5]. For example, the Sun Sensors tell the satellite the sun direction so as to orientate the solar arrays. The Star Tracker provides precise pointing (attitude) needed to take images. Reaction Wheels are used to maneuver the satellite. There are two RF subsystems on-board the satellite, each made up of two redundant chains [6]. The Telemetry and Tele-command (TTC) System receives mission commands from the ground control station and transmits housekeeping data back using S-band frequencies. Image data from the IRIS Camera is transmitted to the ground station using the X-band transmitter (XBT).

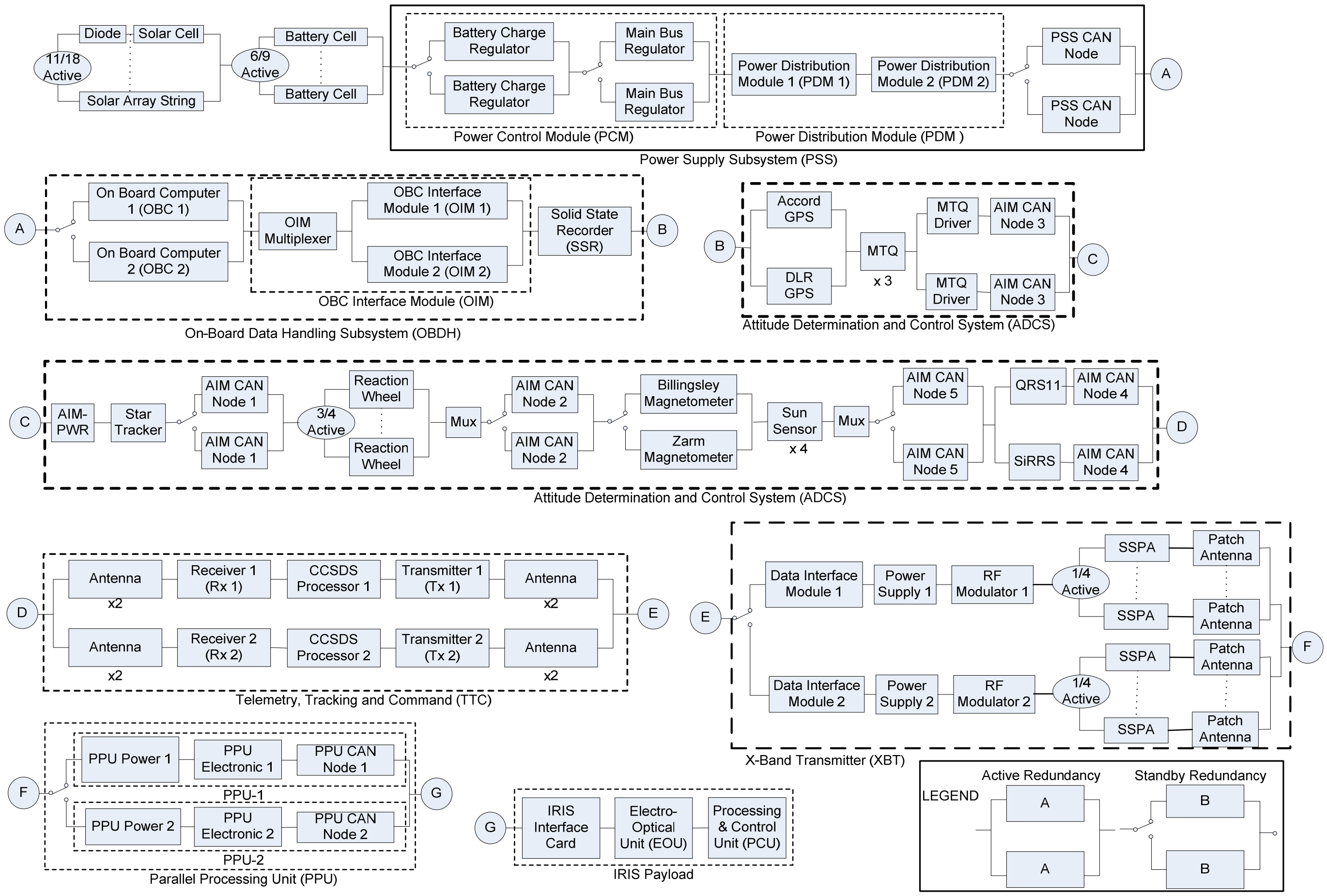


Figure 3: Reliability Block Diagram for the X-Sat Microsatellite

Redundancy is not possible only where there is a constraint imposed by the satellite size and weight e.g. the IRIS camera payload, the star tracker and the satellite structure. Given the volume for the satellite, it is not possible to accommodate a second Camera Head Unit (CHU) for the star tracker, although we have a redundant Data Processing Unit (DPU). As it turns out, the star tracker does not fail, but rather it was not installed in the correct orientation and some stray lights seemed to have entered the star tracker, thereby severely affecting its operations in the day. The satellite can still be manoeuvred for sun-tracking and nadir-pointing. However, the imaging operations in the day can only be done using sensors such as Magnetometer and Sun Sensors. These two sensors give degraded accuracy in attitude information.

4 SCOPE OF REDUNDANCY

The scope of redundancy for X-Sat varies from single component to the entire module [7]. An example of more comprehensive scope of redundancy would be the two complete redundant strings of receiver chain, transmitter chain and CCSDS Processor which made up the TTC subsystem. Where duplicating an entire module or subsystem is not possible due to space and weight constrains, redundancy is incorporated for critical but high failure rate parts such as DC-DC converters in the Power Supply Subsystem or SDRAM in the Solid State Recorder.

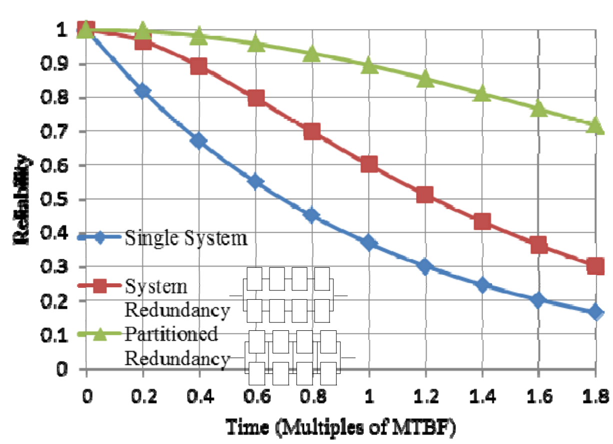


Figure 4: Comparison of System and Partitioned Redundancy

Generally incorporating redundancy at lower assembly level allows us to achieve better reliability. As seen in *Figure 4*, over a longer mission duration (say, >1.5MTBF), the reliability for system redundancy is twice that for single system configuration and the reliability for Partitioned Redundancy is twice that for the System Redundancy configuration. In practice, however, as the switching provisions may not be 100% reliable, this may reduce the reliability benefits somewhat. Failure detection is more difficult and the cost of implementation would have to be considered. System test is also adversely impacted by small scope redundancy. In the example in *Figure 4*, the system with the partitioned redundancy would have required 16 tests compared to 2 for that with system redundancy.

Operational restriction plays an important role in determining the redundancy scheme. The use of cross-strapping between the receiver and transmitter chain would have further improved the reliability of the TTC subsystem (see *Figure **6***). Unfortunately each receiver/transmitter can only work with a dedicated CCSDS process (i.e. receiver 1 with CCSDS processor 1 and not processor 2). This limits the improvement that can be achieved. In addition we require CCSDS processor 1 to send specific instructions to CCSDS processor 2 in order to activate the cold standby transmitter 2.

5 TYPES OF REDUNDANCIES

5.1 Parallel Redundancy

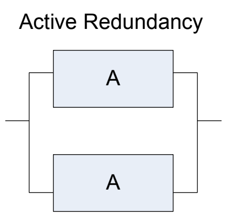
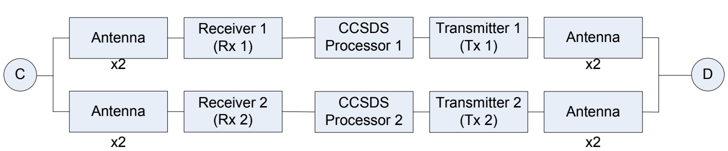
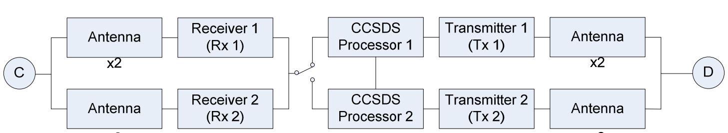


Figure 5: Active Redundancy



(a) Dual Redundant TTC Chains



(b) Cross strapping of Receiver and CCSDS Processor

Figure 6: Reliability Block Diagram for the TTC

In Active Redundancy, external components are not required to perform the function of detection, decision and switching when an item fails (see *Figure 5*). The main and the standby unit will be sharing the load. An example would be the S-band receiver in the Telemetry Tracking and Command (TTC) subsystem as the ability of the X-Sat satellite to listen to any transmission from earth cannot be interrupted (see *Figure **6***) [6]. The advantage is that one needs not be bothered with the reliability of the switching function.

5.2 Standby Redundancy

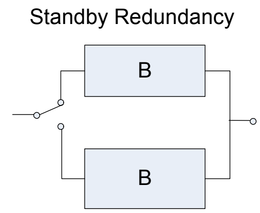


Figure 7: Standby Redundancy

In Standby Redundancy, external elements are required to detect, make a decision and switch to another element as a replacement for a failed element (see *Figure 7*). This is more commonly deployed throughout X-Sat for items such as the On-Board Computer, X-band transmitter (see *Figure 8*) and CAN bus controller. The standby component need not be powered on. This scheme can offer better reliability compared to parallel redundancy.

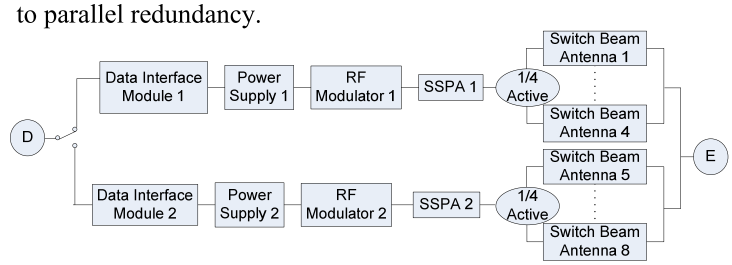


Figure 8: Reliability Block Diagram for the X-band Transmitter

5.3 k/n redundancy

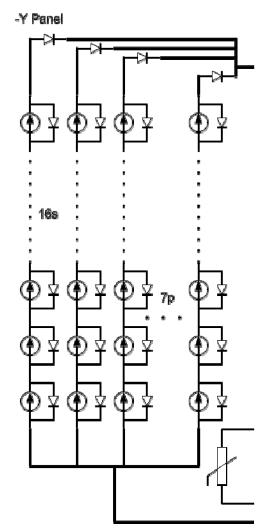


Figure 9: Solar Array Configuration

The k/n redundancy scheme is used for the battery, solar array and memories where failure of any item is replaced by one from a common pool of spares. Batteries and solar arrays are essentially non-redundant but they are sized for the X-Sat end-of-life power requirement [1]. This means the solar arrays and batteries must have sufficient capacity to meet the power requirements for the satellite despite degradation of the solar arrays due to radiation and degradation of the batteries caused by daily charge-discharge cycles.

The solar arrays are mounted on 2 side-deployable panels and one fixed back panel (-Z axis) (see *Figure 1*). These consist of 18 strings with 16 cells in series in each string. A minimum of 14 strings are required to provide sufficient power for imaging. The presence of the bypass diode means that failure of any cell, say open circuit, in an array will result in degraded operation but not loss of an entire string (see *Figure 9*). The blocking diode will prevent discharging of the battery into the solar arrays or into the faulty string.

The battery is configured in 9 strings in parallel with 7 cells in series in each string. Failure of any cell will cause an entire string to fail. The capacity margin for the battery is approximately 33 %, allowing the loss of two strings without any effect on X-Sat operation.

5.4 Same design redundancy

Most X-Sat redundancies are implemented through backup of the same design. This offers protection against random failures but is not very effective against failures due to design deficiencies. If one module fails due to insufficient radiation hardness, the redundant unit is likely to fail soon after. Two units of different design furnishing the same service will offer better protection against failures due to any design deficiencies e.g. the Accord and DLR GPS. The back-up unit usually offers lower accuracy or functionality.

5.5 Analytic Redundancy

Table 2: Types of Analytic Redundancies

Direct	Indirect
Determination of attitude rate from a rate gyro	Observation of celestial bodies by star tracker
Download of image data through X-band transmitter	Download of image data through S-band transmitter
Attitude determination through star tracker	Attitude determination through sun sensor

Analytic (or function) redundancy involves achieving a service through different means (see *Table 2*). It is not modeled in the Reliability Block Diagram. For example, in the event of a complete XBT failure, it might still be possible to transmit images through the TTC subsystem (at reduced data rate of 62.5kbps compared to 50Mbps for XBT). This will degrade the mission, in terms of the image size and download frequency. Another form of analytical redundancy in the X-Sat system is the determination of attitude rate through star trackers (indirect through observation of celestial bodies) instead of from rate sensors (direct).

6 RELIABILITY PREDICTION RESULTS FOR THE X-SAT MICROSATELLITE

The X-Sat microsatellite is required to withstand the g forces, vibration and acoustic environment of a launch and survive for 3 years unattended in the vacuum and temperature extremes of the space environment. The reliability prediction analysis demonstrates that the X-Sat design is able to achieve the reliability goal of 0.7 (see *Figure 10* & *Table 3*).

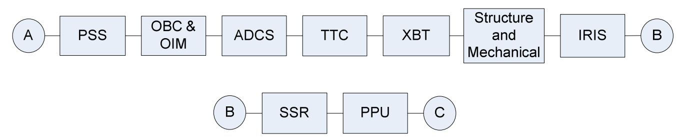


Figure 10: Reliability Block Diagram of the X-Sat Microsatellite (to subsystem level)

$$R_{\text{Image captured \& downloaded}} = R_{PSS} * R_{OBC} * R_{OIM} * R_{ADCS} * R_{TTC} * R_{XBT} * R_{IRIS} * R_{STRUCTURE} \quad (1)$$

Table 3: Reliability Prediction Results for the X-Sat Microsatellite System

	Active λ	Duty Cycle	Effective λ	Reliability
PSS	6.2506	100	6.2506	0.8972
OBDH	1.0740	100	1.0740	0.9737
ADCS	1.6276	100	1.6276	0.9596
TTC	3.3729	2.08	2.4922	0.9366
XBT	0.4521	2.08	0.0486	0.9987
IRIS	4.6843	2.08	0.5561	0.9855
PPU& SSR	1.6700	100	0.1983	0.9948
Structure				0.9903
X-Sat	System	Reliability		0.7602

In orbit, some X-Sat subsystems (i.e. PSS, OBDH, ADCS, and TTC receiver) are powered on all the time while others (i.e. XBT, TTC transmitter, SSR and IRIS Camera) are powered on prior to imaging and powered off once X-Sat leaves the communication area with the Mission Control Station (MCS) of NTU. The distinction between active and passive failure rate ($\approx$ one tenth the active rate) is important for X-Sat as the duty cycle for some subsystems is as small as 2.08%. This duty cycle is obtained by assuming that there is an average of 2 good passes per day (out of 15) and that each pass lasted 15 min. The effective failure rate (λ) is assumed to be dependent on the duty cycle (DC) and obtained as follow:

$$\lambda_{\text{effective}} = DC * \lambda_{\text{Space active}} + (1\text{-}DC) * \lambda_{\text{Dormant}} \quad (2)$$

High reliability subsystems are those with modules on stand-by redundancies and low duty cycles (e.g. TTC, IRIS, and XBT).

CONCLUSION

At the time of writing this paper, X-Sat has operated in space for about 18 months without hardware failure, saved for a number of radiation induced upsets and latch-ups. The approach to building redundancy as much as possible to deal with single-point-failure and implementing it via parts or complete module level appears to be a reasonable approach for such a micro-satellite program. There were a number of design related issues, the key one being the incorrect orientation of the star tracker. By and large, X-Sat is still able to capture images as intended although the pointing was not accurate. In addition, the captured imagery data can be down linked within the same imaging pass The largely successful overall mission of X-Sat in space operations shows the effectiveness of achieving hardware reliability through stringent parts selection policy, derating, and environmental stress screening. Should a failure eventually occur, the extensive redundancy scheme (hot, cold or k/n redundancies) deployed on-board the X-Sat microsatellite system will allow us to achieve the mission life of three years required. Factors that may curtail its operational life such as radiation induced degradation have been taken care of by appropriate sizing of the solar array to account for degradation in cell efficiency and sizing of the battery with sufficient capacity to meet the End-of-Life (EOL) power demand of the satellite.

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