EVALUATION OF THE EFFECTIVENESS, PERFORMANCE AND INTEGRITY OF SUNSAT'S TELEMETRY SYSTEM

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

ABSTRACT

In February 1999, SUNSAT, a university developed satellite was launched for the purposes of amateur communications. The effectiveness, performance and integrity of SUNSAT's telemetry is evaluated in this thesis. Analytical data for the evaluation of SUNSAT's telemetry could not be compiled since SUNSAT is currently functional in space. SUNSAT is limited in its functions in its present role. Hence, future roles of SUNSAT were proposed and investigated and the effectiveness, performance and integrity in these new roles evaluated based on the findings in technical articles on similar topics. These future roles proposed include SUNSAT as a multi-satellite with multiple groundstation configuration. An integrity checking system was investigated and proposed to ascertain the validity of telemetry received as well as a software package to evaluate the performance of SUNSAT.

OPSOMMING

In Februarie 1999 was a universiteits-ontwikkelde satelliet, SUNSAT, gelanseer met die aanvanklike doel van amateur kommunikasie. Die effektiwiteit, werkverrigting en integriteit van SUNSAT se telemetrie word in hierdie verhandeling getoets. Analitiese data van SUNSAT se telemetrie kon nie saamgestel word nie weens die feit dat SUNSAT sedert Februarie 1999 operasioneel is. Huidiglik is SUNSAT se funksies beperk en toekomstige funksies en rolle daarvan was nagevors en voorgestel. Hierdie nuwe funksies was getoets gebaseer op bevindinge in tegniese artikels op soortgelyke onderwerpe. Toekomstige funksies sluit in die gebruik van SUNSAT as 'n multi-satelliet met die opstelling van veelvuldige grondstasies. Navorsing is ook gedoen op 'n integriteits-toetsing stelsel, asook 'n sagteware pakket om die werkverrigting van SUNSAT te toets. Hierdie integriteits-toetsing stelsel is voorgestel om die geldigheid te bepaal van alle telemetrie wat ontvang word.

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TABLE OF CONTENTS

1 INTRODUCTION 1
2 AMATEUR SATELLITES AND THEIR TELEMETRY SYSTEMS 4
2.1 AMATEUR AND MICROSATELLITES 4
2.2 TELEMETRY SYSTEMS ON AMATEUR SATELLITES 6
2.3 USES OF TELEMETRY DATA 10
2.4 TELEMETRY DATA FORMAT STANDARDS 11
2.5 TELEMETRY DATA RECEIVING SOFTWARE 11
3 SUNSAT-1R 12
3.1 INTRODUCTION 12
3.2 PURPOSE OF THE TELEMETRY SYSTEM 13
3.3 DESIGN PHILOSOPHY 13
3.4 HARDWARE DESIGN REQUIREMENTS 13
3.4.1 Hardware And Software Based Telemetry Function 14
3.4.2 Reliability 14
3.4.3 Flexibility 15
3.4.4 Data Security 16
3.4.5 WOD 16
3.4.6 Dwell Facility 18
3.4.7 Power Consumption 18
3.5 THE TELEMETRY FUNCTION 18
3.6 THE MINIMUM TELEMETRY SYSTEM 22
3.7 THE ON-BOARD COMPUTERS 24
3.7.1 The Telemetry System Microcontroller 24
3.7.2 Data Transmission Hardware 26
3.8 SUNSAT 1R – FRAME STRUCTURE 27
3.9 DATA SYNCHRONISATION 28
4 EVALUATION OF THE EFFECTIVENESS, PERFORMANCE AND INTEGRITY OF SUNSAT'S TELEMETRY SYSTEM 29
4.1 PRESENT SUNSAT-1R TELEMETRY 29
4.1.1 Synchronisation of Clocks for Frame Counter 29
4.1.2 Masking of Last Byte in Telemetry Frame 30
4.1.3 Power supply 30
4.1.4 Cable Harness 31
4.1.5 Protection of Analog Outputs to Buffers / Analog to Digital Converters 31
4.2 EVALUATION OF SUNSAT-1R IN PRESENT ROLE 32
4.3 PROPOSAL AND INVESTIGATION OF OTHER ROLES FOR SUNSAT 32
4.3.1 Performance of SUNSAT as a Two-Layer Satellite Communication Network 32
4.3.1.1 Introduction 32

4.3.1.2 Assumptions and Operation ... 34
4.3.1.3 Analysis ... 36
4.3.1.4 Numerical Examples and Discussion ... 38
4.3.2 Performance Analysis and Simulation Study for SUNSAT as a Variable-Channel-Per-Burst SS-TDMA with Multiple Groundstations ... 40
4.3.2.1 Introduction ... 40
4.3.2.2 VCPB Advantageous Traffic Domain ... 42
4.3.2.3 Reconfiguration Process ... 44
4.3.2.4 Reconfiguration Strategies ... 47
4.3.2.5 Performance Analysis ... 48
4.3.2.6 Reconfiguration Probability ... 50

4.4 PROPOSAL AND INVESTIGATION OF SYSTEMS FOR EVALUATION OF SUNSAT ... 51
4.4.1 Proposal and Investigation of Integrity Checking System for SUNSAT ... 51
4.4.1.1 Introduction ... 51
4.4.1.2 Integrity Checker for SUNSAT's Subsystems ... 52
4.4.2 Proposal and Investigation of a Software Package for the Performance Evaluation of SUNSAT with Adaptative Allocation of Onboard Common Resources ... 54
4.4.2.1 Introduction ... 54
4.4.2.2 System Parameters ... 55
4.4.2.3 The software package ... 56

5 PROPOSALS ... 58

5.1 AN FPGA-BASED APPROACH TO THE COMPACTING OF THE SUNSAT-1R TTM SYSTEM ... 58

5.2 PROPOSED SUNSAT-2R SYSTEM ARCHITECTURE ... 59

5.3 USE OF FPGAS ... 61
5.3.1 Choice of FPGA ... 61
5.3.2 What are FPGAs? ... 61
5.3.3 Design Entry Method ... 62
5.3.4 Radiation Hazard ... 62
5.3.5 SRAM versus Anti-Fuse ... 63
5.3.6 Total Dose Effects on FPGAs ... 65
5.3.7 SEU and SEL of FPGAs ... 67
5.3.8 Conclusion on Choice of FPGA ... 68

5.4 PROPOSED FPGA AND MICROPROCESSOR ON ONE SILICON CHIP ... 70
5.4.1 Telemetry Subsystem Hardware ... 70
5.4.1.1 FPGA Logic Configuration ... 72
5.4.1.2 Telemetry System Function Performing Block ... 72
5.4.2 Decentralised Telemetry ... 73

5.5 CONCERNS AND ADVANTAGES OF THE NEW ARCHITECTURE ... 74

6 CONCLUSION ... 75

LIST OF FIGURES

Figure 1.1 - A Typical Satellite Telemetry System 1
Figure 2.1 - Basic Construction of A Microsatellite 5
Figure 2.2 - Typical Implementation of Telemetry and Telecommand Systems 8
Figure 2.3 - A Sequential Scanning Telemetry System 9
Figure 3.1 - Prototype Model - Functional Block-diagram 19
Figure 3.2 - The Decentralised Implementation 20
Figure 3.3 - Block-diagram of Prototype Model 21
Figure 3.4 - Asynchronous Data Format 23
Figure 3.5 - Implementation of a MTS 23
Figure 3.6 - Telemetry Microcontroller System 25
Figure 4.1 - Proposed Future SUNSAT Two-Layer Satellite Network Architecture 33
Figure 4.2 - Cell Layout 37
Figure 4.3 - Proposed Future SUNSAT SS-TDMA System With Onboard Baseband Switch 40
Figure 4.4 - Burst Configurations 43
Figure 4.5 - System Function Required for Reconfiguration 45
Figure 4.6 - Channel Assignment Algorithm 48
Figure 4.7 – Proposed Future Generation SUNSAT Architecture 52
Figure 4.8 – Integrity-Checker-Centred Processes for SUNSAT Groundstation 53
Figure 5.1 - Complete SUNSAT 2R Architecture 59
Figure 5.2 - Generic Building Block Architecture 60
Figure 5.3 - FPGA and Microprocessor on One Custom Silicon Chip and Telemetry System Function Performing Block 71
Figure 5.4 - Decentralised Telemetry Structure 73

LIST OF ABBREVIATIONS AND ACRONYMS

ADC	Analog to Digital Converter
ASIC	Application Specific Integrated Circuit
BAUD	Unit of measure for Bits per second
BBSW	Baseband Switch
BS	Base Station
C&C	Command & Control Processor
CMOS	Complementary MOS
DAC	Digital to Analog Converter
DC	Direct Current
DSP	Digital Signal Processor
EOC	End of Conversion
EPROM	Electrical Programmable Read Only Memory
FCPB	Fixed-channel-per-burst
FPGA	Field Programmable Gate Array
GEO	Geostationary Earth Orbit
HC	High-speed CMOS
IC	Integrated Circuit
IO	Input / Output
LEO	Low Earth Orbit
LSB	Least Significant Bit
MSC	Mobile Switching Centre
OBC	On-Board Computer
PCN	Personal Communications Network
PCS	Personal Communications System
RAD	Radiation Absorbed Dose
RAM	Random Access Memory
RDISK	RAM Disk

RF	Radio Frequency
ROM	Read Only Memory
RTDB	Real-time database
RTS	Real-time system
SCPB	Single-channel-per-burst
SEE	Single Event Effect
SEL	Single Event Latchup
SEU	Single Event Upset
SS-TDMA	Satellite-Switched Time Division Multiple Access
SUNSAT	Stellenbosch University Satellite
TD	Total Dose
TDMA	Time Division Multiple Access
TMS	Telemetry and Modems System
TTMS	Telecommand, Telemetry and Modems System
UART	Universal Asynchronous Receiver / Transmitter
VCPB	Variable-channel-per-burst

1 INTRODUCTION

SUNSAT, a low earth orbit (LEO) satellite needs a reliable and flexible telemetry system for a successful mission. With the spacecraft "out of reach" of the operator left on earth, the telemetry system becomes the remote eye, performing the essential task of monitoring the satellite's status in orbit.

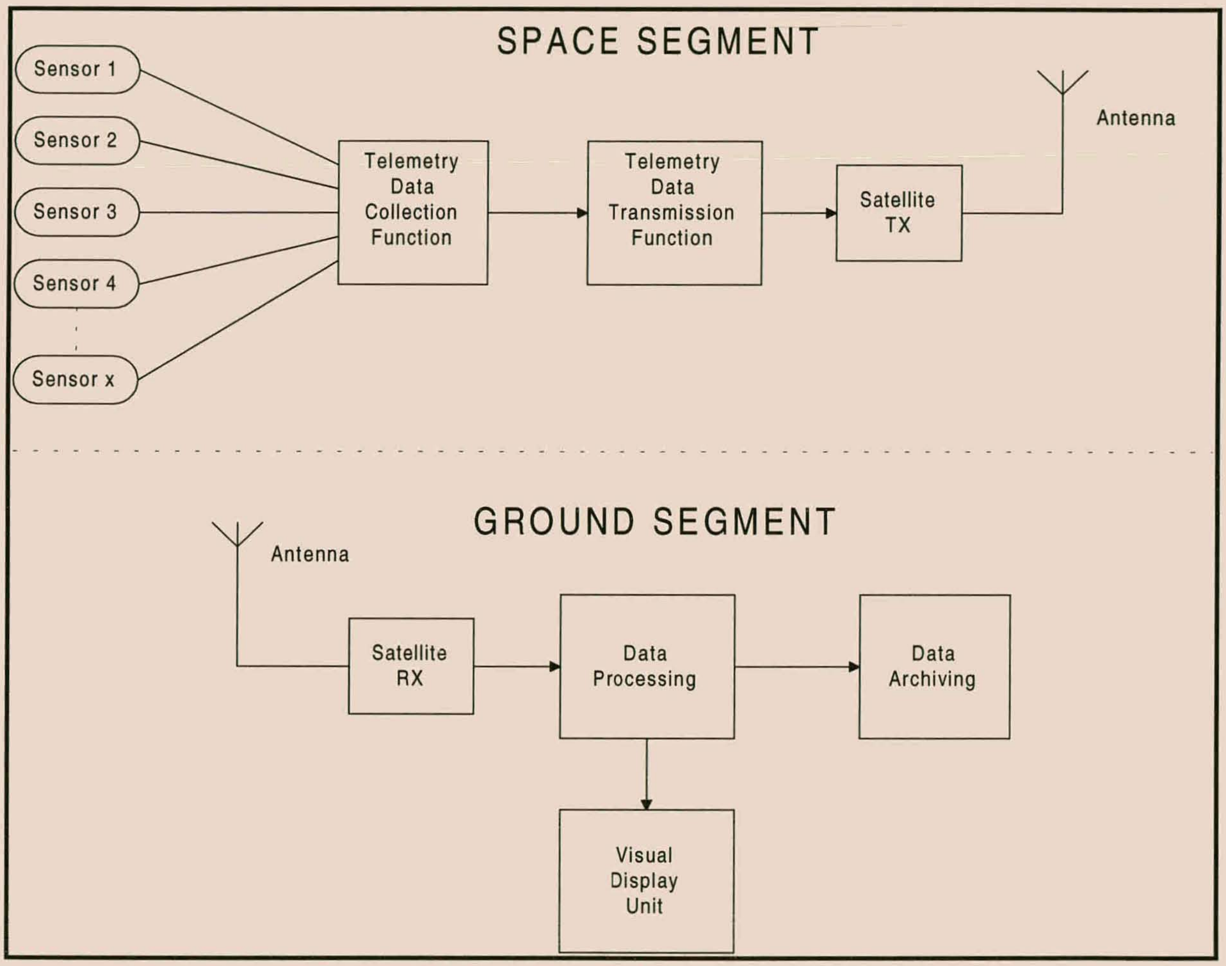

Figure 1.1 - A Typical Satellite Telemetry System

Figure 1.1 shows a block-diagram of a typical telemetry system for an amateur satellite. The system consists of a space segment which is located on-board the satellite and the ground segment which is located in the Ground Control Station. The space segment consists of a data collection and a data transmission function.

The data collection function collects data from various sensors in the satellite and converts them into digital format. Some examples of these include voltage, current and temperature. The data transmission function converts the data into a suitable format for transmission. The satellites transmitter in turn transmits this information to the Ground Control Station.

The ground segment has two main functions. The first being the receiving, decoding and displaying of the data in such a manner so that the satellite operator can easily determine the status of the satellite. The second function is to archive the data for later use. This archived data can be used to analyse trends in the satellite's behaviour over periods longer than one orbit. [1]

The effectiveness, performance and integrity of SUNSAT's telemetry is evaluated in this thesis. Analytical data for the evaluation of SUNSAT's telemetry could not be compiled since SUNSAT is currently functional in space. SUNSAT is limited in its functions in its present role. Hence, future roles of SUNSAT were investigated and proposed and the effectiveness, performance and integrity in these new roles evaluated based on the findings in technical articles on similar topics. These future roles proposed include SUNSAT as a multi-satellite with multiple groundstation configuration. An integrity checking system was investigated and proposed to ascertain the validity of telemetry received as well as a software package to evaluate the performance of SUNSAT.

This document is arranged as follows:

Chapter 2 is a qualitative description of amateur satellites and their telemetry systems.

Chapter 3 describes the functions of SUNSAT-1R from a systems point of view.

Chapter 4 evaluates the effectiveness, performance and integrity of SUNSAT in its present and future role.

Chapter 5 proposes a new SUNSAT-2R system architecture and a FPGA approach to compacting SUNSAT's telemetry system.

Chapter 6 summarises and concludes the findings of this thesis.

2 AMATEUR SATELLITES AND THEIR TELEMETRY SYSTEMS

2.1 AMATEUR AND MICROSATELLITES

Amateur satellites are microsatellites that carry Amateur Radio payloads. Currently there are many of these satellites in low earth orbit (LEO). Microsatellites are relatively small as compared to commercial satellites. The average amateur satellite weighs between 30 kg to 60kg while commercial communication satellites could weigh up to several tons.

Microsatellites are usually built with experimentation and education as the main objectives. Typical experiments include studies in satellite communications, space science, space education and spacecraft engineering.

The cost of developing a microsatellite is usually only in the reach of educational institutions such as universities and amateur radio organisations such as AMSAT and institutions such as the University of Surrey whose series of UoSat's (University of Surrey Satellite Project) spacecraft are well known to satellite experimenters.

Since these amateur satellites are small and light, they can be launched as auxiliary payloads together with larger commercial satellites. Usually several amateur satellites are launched together with one large satellite. This is beneficial to the developers as the cost of launching is divided between several projects. Sometimes the cost of the launch is totally covered by the developers of the primary satellite.

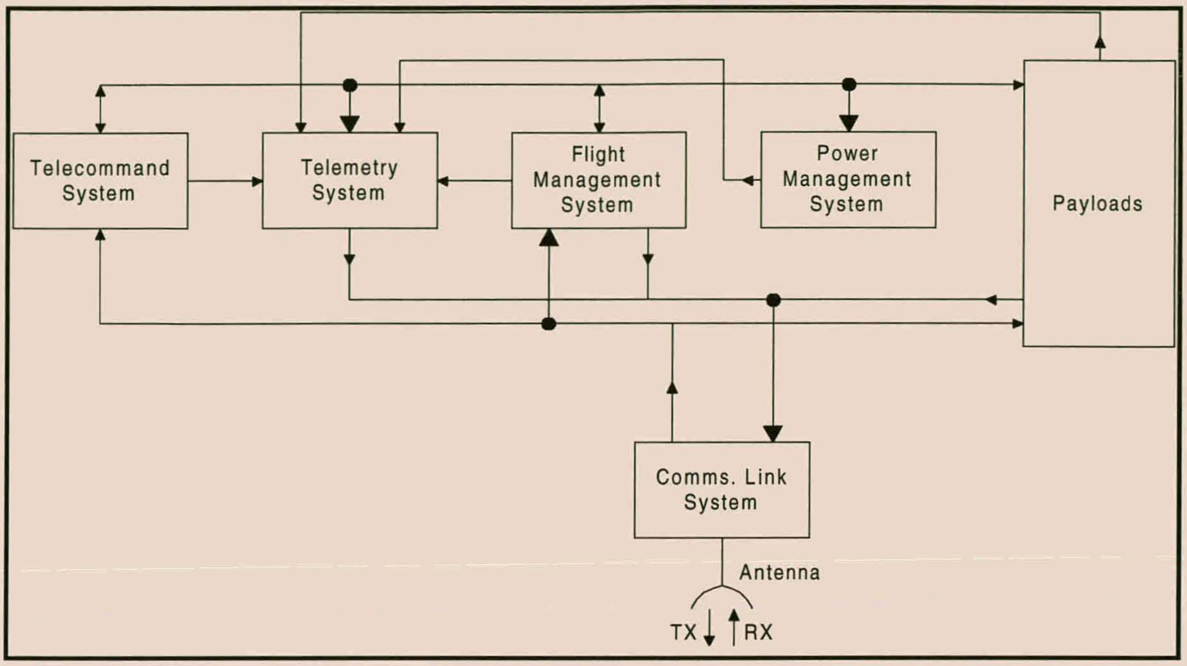

Figure 2.1 - Basic Construction of A Microsatellite

Figure 2.1 shows a block diagram of the basic subsystems of a microsatellite. The Comms Link System provides the communications links required for communication with ground stations. All communications take place through this system. The Telecommand System controls the satellite's bus and payloads through a series of telecommand signals. The Telemetry System monitors the status of all the subsystems and transmits the data through the Comms Link System. The Flight Management System performs basic satellite control and housekeeping through the Telecommand System. The payloads are usually experiments such as imagers or experimental communication systems.

Communications with amateur satellites is divided into three categories. These are experimental communications, the transmission of commands and data to the satellite and the transmission of satellite information (telemetry data) from the satellite. Amateur satellites carry amateur radio payloads that enable users to experiment with space communications, different protocols and communication systems such as store and forward systems. These communications are classified as experimental communications.

Apart from the amateur radio payloads, the satellite must be able to communicate with the satellite's Ground Control Station. This station controls the satellite's mission through the satellite's telecommand system. Communication from the Ground Control Station to the satellite will include commands for different subsystems as well as programme data. Finally, all satellites must transmit telemetry data to enable the control station to determine the status of the satellite and to monitor the effect of commands sent to the satellite. [1]

2.2 TELEMETRY SYSTEMS ON AMATEUR SATELLITES

Telemetry can be defined as the transmission of inaccessible data to accessible locations. Telemetry and telecommand systems provide the essential capability of remote monitoring and control of a satellite's functions once in orbit. With the spacecraft "out of reach" of the operator left on Earth, these two subsystems become their remote eyes and hands to manipulate the satellite's subsystems and payloads to the best advantage. The telemetry and telecommand systems must exhibit an exemplary level of integrity and reliability, whilst retaining a maximum of flexibility to respond to diverse in-flight problems or failures. In the event of failures on board the spacecraft, the telemetry and telecommand systems should be the last to succumb and their design must reflect this requirement.

The telemetry system has to be designed to provide comprehensive "housekeeping" information on the status and performance of all the spacecraft's operational functions during both normal and anomalous activities. The basic requirements may be summarised as follows:

- to provide the maximum of information on the satellite's systems;
- to operate with a very high degree of reliability;
- to yield data with high integrity;
- to exhibit a high degree of flexibility of configuration;
- to consume minimal power;
- to be compatible with inexpensive ground-station equipment.

The satellite operator at the Ground Control Station analyses the data to determine if anything is wrong, and if so what corrective action to take. The actions are then encoded into one or more telecommands. The commands are transmitted to the satellite where the telecommand system will initiate the corrective actions. Figure 2.2 below is a graphical representation of this process.

Current amateur satellites implement telemetry systems that sequentially scan through the telemetry data channels, sampling each channel periodically. A telemetry channel is a single sensor (or transducer) on board the satellite that measures one of the satellites variables. The sampling process results in a series of discrete samples from the different sensors. One set of samples (one sample from each sensor being monitored) is packed together sequentially in a "telemetry data frame".

Telemetry data from amateur satellites can be in the form of analog or status data. An analog channel is usually in the form of a continuous analog signal. Temperature and current are two possible examples of analog channels. An analog-to-digital converter is used to convert the analog signal to a digital format.

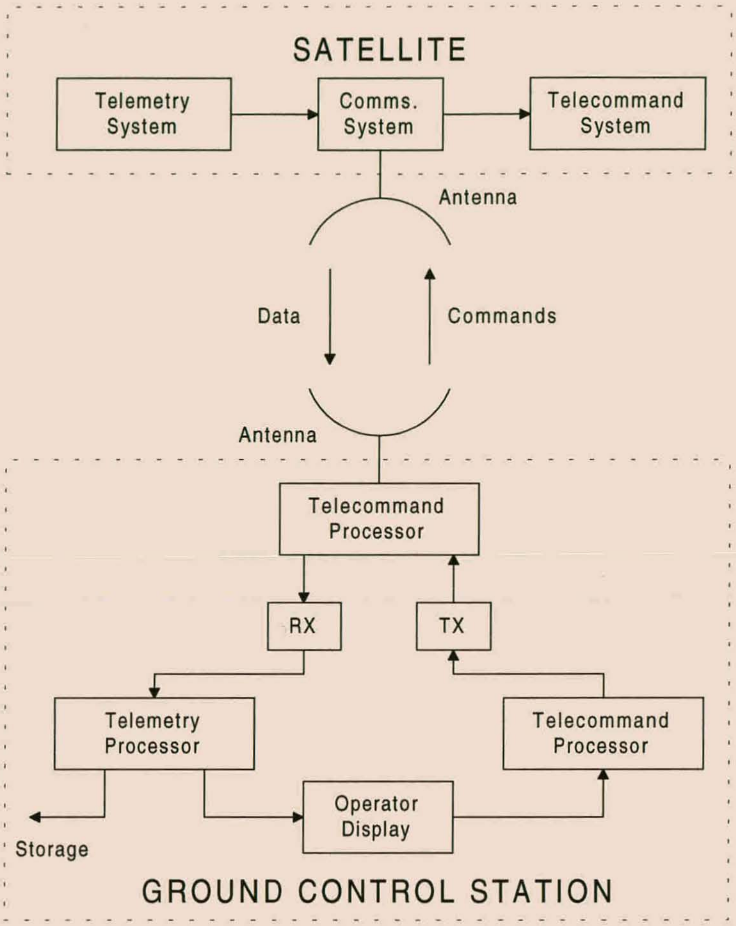

Figure 2.2 - Typical Implementation of Telemetry and Telecommand Systems

Status telemetry data indicates the status of a telemetry channel that can only have one of two states. The status signal is in a digital format and can be represented by a single data bit.

Figure 2.3 shows a block-diagram of a typical telemetry system that sequentially samples data from different telemetry channels. The inputs from the sensors are time multiplexed by two multiplexers. These time multiplexers also serve as samplers. The analog to digital converter converts the analog telemetry data to digital format. The data is again time multiplexed into the data formatter which converts the data to a format which is usable by the on- board computer. The on-board computer collects the data from the telemetry system, processes the data if required and transmits on request or at set intervals.

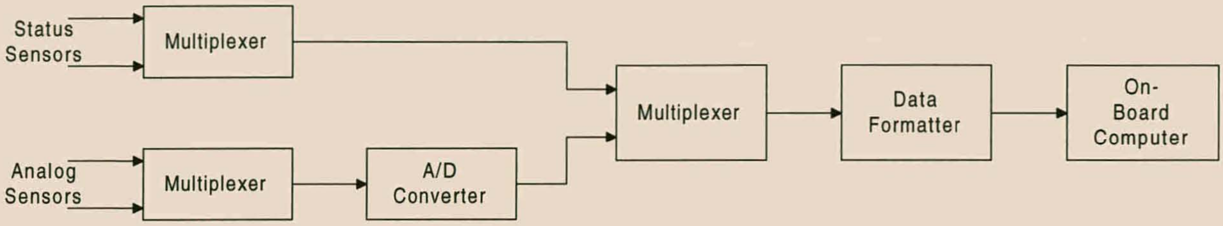

Figure 2.3 - A Sequential Scanning Telemetry System

Some of these amateur microsatellite telemetry systems implement a dwell facility, which enables the system to dwell on a single or a small set of selected telemetry channels instead of scanning through all the channels. Since the telemetry system is only sampling a single or small set of channels, the sampling rate is fixed and the channels can be sampled more frequently and therefore a better time resolution is obtained. Such a facility is usually used for the analysis of some subsystem that is not functioning correctly.

Some telemetry systems implement a Whole Orbit Data (WOD) facility. WOD is collected during one or more complete orbits and provides a more complete picture of the satellite's operations and characteristics. Since these amateur satellites are in LEO, they are out of sight of the control station for most of the time. WOD allows the control station to see the actions on board the satellite while it was out of sight. The WOD is usually collected by the on-board computers and dumped when the satellite passes over the control station.

Collecting WOD can result in a huge amount of data being stored in the on-board computer's memory. The satellite controller is only interested in a few critical and vital data channels. To minimise the telemetry data memory storage area, only these channels are stored. To further minimise the amount of memory used, some of the sampled data is discarded. This results in the time between samples being much longer than in the case of "real-time" data. Since the period of data collection is much longer than with "real-time" data, it is not necessary to have such a good time resolution and discarding some of the samples does not have a serious effect on the accuracy of the data. Since a processor collects the data, it is possible for the processor to process the data before discarding some of the samples. It could, for example, compute the average of a few samples and only store the average values. [1]

2.3 USES OF TELEMETRY DATA

The most important use of data gathered from the telemetry system is in the daily housekeeping of the satellite. The satellite operator can determine the satellite's status as it passes over the ground control station. If necessary, corrective actions can then be undertaken.

Telemetry data from satellites is analysed to determine long term trends in the satellite's characteristics. The ground control station, other researchers and experimenters (including radio amateurs) are interested in long term trends since it provides information used for long term planning of missions as well as the planning of successive missions. It also gives some valuable information on the characteristics of the satellite.

The analysis of telemetry data also provides information on the space environment and its effect on components and systems. Another group of people who are interested in telemetry data are the experimenters that are involved in microsatellite programmes. These experimenters use the telemetry data as a means of transmitting information about experiments on board the satellite.

2.4 TELEMETRY DATA FORMAT STANDARDS

Simple data transmission formats are usually employed for the telemetry systems on board amateur satellites. One of the main objectives of these satellites is to educate people about space communications. Use of simple data formats allow people to write their own software to receive and decode telemetry with minimal amount of ground station hardware.

2.5 TELEMETRY DATA RECEIVING SOFTWARE

There are different formats in which telemetry data is transmitted by different satellites. Hence there is a large variety of telemetry receiving software currently available for the reception, decoding and displaying of telemetry data from different satellites. Most of this software is satellite specific. However, there are some software packages that will receive and decode data for more than one satellite.

3 SUNSAT-1R

Overview

SUNSAT-1R is analysed in this chapter using the thesis of I. De Swart, "A Telemetry System for SUNSAT", (September 1994) as the source document.

3.1 INTRODUCTION

SUNSAT-1R is a 450mm X 450mm X 600mm, 60 kg Low Earth Orbit (LEO) satellite. The major components of SUNSAT-1R consists of:

- Solar panels on all 4 sides and re-chargeable Nickel-Cadmium batteries
- On-board computers : 80C188 and '386 as in personal computers
- Telecommand and telemetry equipment to monitor and control the satellite
- Attitude determination with horizon, sun and star sensors as well as a magnetometer
- Orientation control with reaction wheels, magnetorquers and a gravity gradient boom
- Communication transmitters, receivers and antennas
- High resolution camera that photographs the earth in stereo and colour
- Structure with attachment and release mechanisms to the launch rocket
- Numerous software programs in the satellite as well as in the ground-station
- NASA's GPS hardware

SUNSAT-1R was launched in February 1999 by NASA from the Vandenberg Air Force Base in California, USA. The launch vehicle was a DELTA II rocket during mission P-91.

3.2 PURPOSE OF THE TELEMETRY SYSTEM

The purpose of the telemetry system on board SUNSAT-1R is to measure both analog and status channels of the satellite and transmit these measurements to the ground-station under all operational conditions. Figure 1.1 shows a typical implementation.

3.3 DESIGN PHILOSOPHY

SUNSAT-1R's telemetry system was developed in three design phases. The first stage was the prototype design that consisted of a conceptual design, and a prototype model. The model tested the functionality of the conceptual design. The hardware developed in this phase did not have to physically resemble the subsystem that will eventually be used in the flight model.

The second stage was the engineering design phase. This phase was used to refine the concepts tested by the prototype model. The engineering model resembles the flight model in size, basic design and layout.

When the engineering model satisfied all the design requirements, the flight model was developed. [1]

3.4 HARDWARE DESIGN REQUIREMENTS

The main design requirements for SUNSAT-1R's telemetry system were:

- Both hardware and software based telemetry functions must be implemented.

- Reliability to perform the telemetry function under all operational conditions.
- Flexibility to adapt to different situations.
- It must collect both analog and status telemetry.
- The data formats and transmission protocols must comply with current developing standards.
- A WOD (Whole Orbit Data) facility must be implemented.
- A dwell facility must be implemented.
- Minimum power consumption.
- Minimum weight and size.

3.4.1 Hardware And Software Based Telemetry Function

The telemetry system must not rely on a software based telemetry design to implement the telemetry function. Provision was made for a hardware based telemetry system that did not rely on any on-board processors to perform its function. This was done to increase the reliability of the system, since processors are very susceptible to failure in the space environment.

3.4.2 Reliability

Reliability is the main requirement for a satellite telemetry system. SUNSAT-1R is a "low budget" experimental satellite. Non-military standard components were used in the implementation of most of its subsystems.

Reliability can be enhanced through various means. Redundancy is the most obvious example. However, redundant subsystems impose weight as well as space constraints to the system. Therefore redundancy was used discretely as a means of improving reliability.

Another way to improve reliability was to use components from different manufacturers. This allows the designer to increase reliability in a design that already uses redundancy.

3.4.3 Flexibility

The telemetry system must be a flexible system that can respond to different operational situations, needs, in-flight problems and failures experienced during the satellite's mission. The Flight Management System and the satellite operator must be able to configure the telemetry system to adapt to these different operational situations.

The design of the telemetry system must anticipate the failure of one or more of the satellite's subsystems. It must specifically consider the situation in which all the microprocessors on board the satellite have failed.

The telemetry system must also anticipate the need to transmit data in different data formats. The ability to transmit data in different formats will allow the implementation of different standards for the format used in the downlinking of telemetry data. The data transmission format must be upgradeable after the satellite has been launched into orbit. This will make the satellite compatible with possible future standards.

The system should also be able to use different protocols for the transmission of the telemetry data. One example is the transmission of data using a basic format and simple protocol that can be received by anyone with a minimum of ground station equipment. This will be ideal for schools or individuals who don't have the money to set up a complete satellite ground station. Since personal computers are readily available and different data formats can be easily decoded on such computers, the exact data formats are not of importance.

To further increase the flexibility, the telemetry system must be able to sample the telemetry points at different sampling speeds. This feature will be used when telemetry data with a high time resolution is required, e.g. for fault finding if something should go wrong on the satellite. The use of the dwell facility will extend the ability of the system to sample at different sampling rates.

3.4.4 Data Security

Some satellite developers do not want to make their satellite's telemetry data available to the public. These satellites use some sort of security mechanism to protect their telemetry data. This protection is not necessary on SUNSAT since the designers wish to make the satellite's data available to anyone who is interested in it.

3.4.5 WOD

SUNSAT orbits in a LEO with an altitude of approximately 800km. In this orbit the satellite will be out of sight of the control station for most of its operational life. Typically it will only be visible for 40 to 45 minutes per day. Some activities on board the satellite will be scheduled for when the satellite is out of sight of the Ground Control Station. In most cases the telemetry data is the only way to see whether these activities were executed successfully. There exists a need for the control station to obtain this telemetry data.

Telemetry data could be collected from radio amateurs around the world to enable the control station to form a more complete picture of the satellite's status as it orbits around the earth. However, this is not an ideal situation since the Ground Control Station will have to depend on other ground stations tracking the satellite. Another problem with this approach is that the satellite passes over large oceans where there are no stations that can track the satellite. The data collected in this way will not be sampled at regular intervals and there will be large gaps in time.

A more ideal situation is to have a Whole Orbit Data (WOD) capability that enables the telemetry system to collect data continuously as it orbits the earth. When the satellite passes over South Africa, the WOD can be dumped as a single data file. The dumping of the data can happen automatically when the satellite passes over the Ground Control Station or it can be dumped on request from any ground station. After the data is dumped, it can then be decoded and analysed to obtain a more complete picture of the satellite's operations and characteristics.

The data that is typically collected as WOD is attitude determination data and data on the power system (specifically the batteries and load currents) as well as the monitoring of critical activities.

The WOD capability will require memory storage that is large enough to store data samples for at least one complete orbit and preferably for several orbits. Usually only a selected few channels will be monitored for the collection of WOD and only at a much slower sampling rate (typically 1 sample for every 5 minutes). This eases the requirement on the storage space for WOD.

3.4.6 Dwell Facility

The use of a dwell facility enables the telemetry system to produce telemetry data with a higher time resolution compared to sequential scanning since fewer channels are sampled at the same sampling rate. Ideally the channels that the telemetry system dwells on must be software selectable. This facility will have to be implemented with the help of one of the on-board computers.

3.4.7 Power Consumption

The telemetry system will be powered continuously during the satellite's mission. Therefore it must consume a minimum amount of power. This can be accomplished by using low power technologies such as CMOS for the design.

3.5 THE TELEMETRY FUNCTION

The telemetry function is divided into the data acquisition, data collection and data transmission functions. The data acquisition function combines the telemetry information from the different satellite trays and presents it to the data collection function in digital format. The data collection function selects the required information, arranges it in some defined format and stores the data. The transmission function is to take the collected telemetry data and present it to the modems in a format suitable for transmission via a modem and transmitter. Figure 3.1 illustrates these different functions.

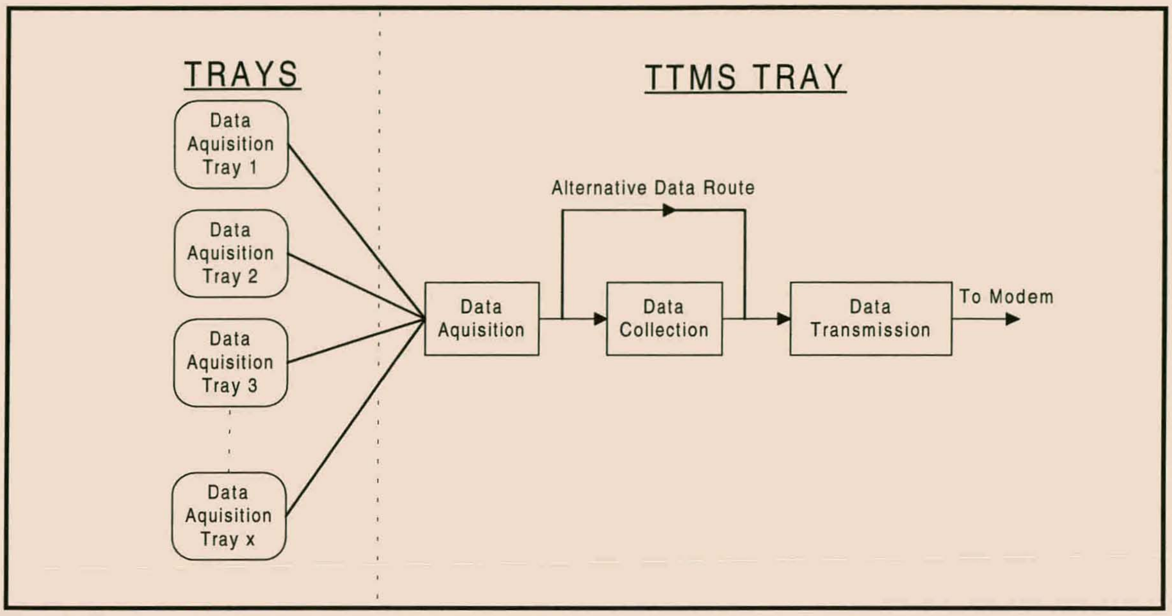

Figure 3.1 - Prototype Model - Functional Block-diagram

This telemetry system hardware is implemented as a decentralised system with data acquisition hardware situated on each of the satellite's trays and data acquisition, collection and transmission hardware on the TTMS (Telemetry, Telecommand and Modems) tray. Figure 3.2 is a block diagram of the decentralised implementation. It shows 8 satellite trays with a signal path between each tray and the TTMS tray.

Each signal path carries two streams of data, one analog and one digital, from the client tray to the telemetry system. The signal path also carries control signals from the TTMS tray to the acquisition hardware on the client trays.

Figure 3.3 shows a simplified block-diagram of the hardware on the TTMS tray along with the data acquisition hardware from one client tray. The data acquisition hardware on each tray will combine the telemetry data from that tray into two serial data streams.

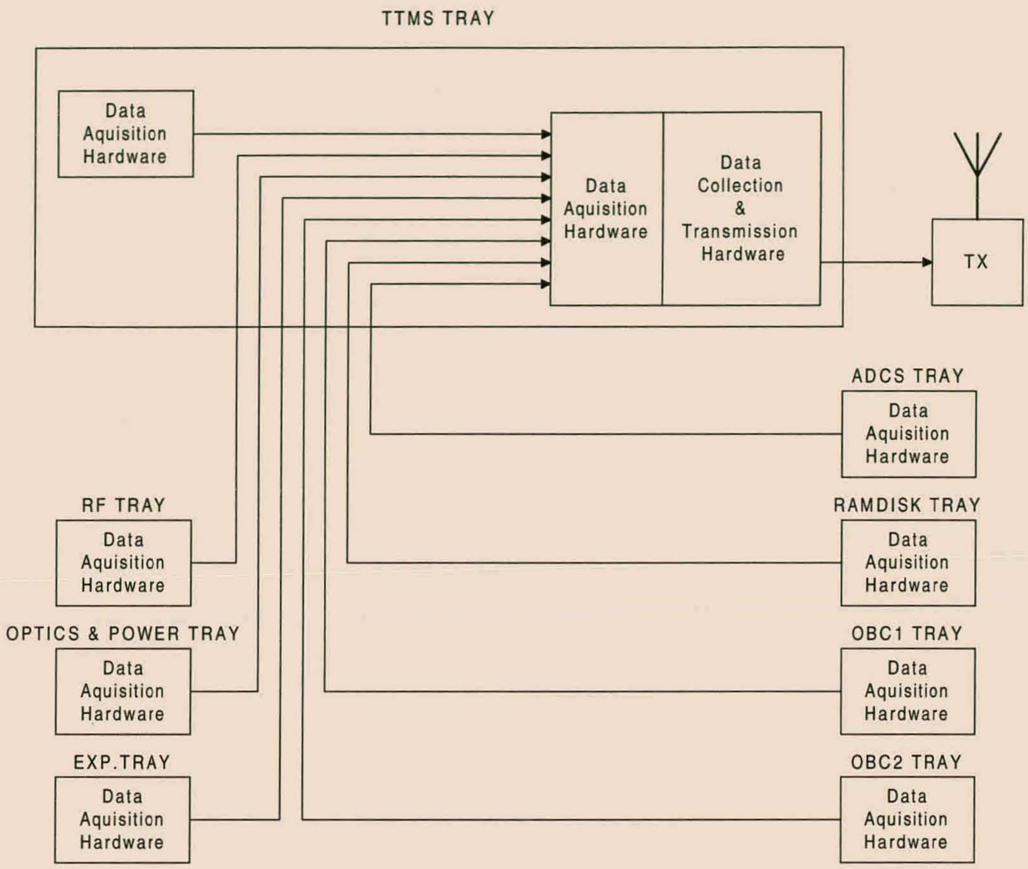

Figure 3.2 - The Decentralised Implementation

These data streams are then input by the acquisition hardware (combiner modules) on the TTMS tray. These combiner modules combine the data streams from the 8 trays and convert the analog data to digital format. The digital data is then sent to the data collection hardware that consists of an 8-bit microcontroller and two on-board computers.

The OBC's are not part of the telemetry system, but software on these processors will enable them to perform the telemetry data collection and transmission functions. The microcontroller or the on-board computers, depending on which processor is used for data collection implement the transmission function hardware. The telemetry system hardware is controlled through the telecommand system. The satellite operator as well as the Flight Management

System can control the telecommand system and thus the configuration of the telemetry system.

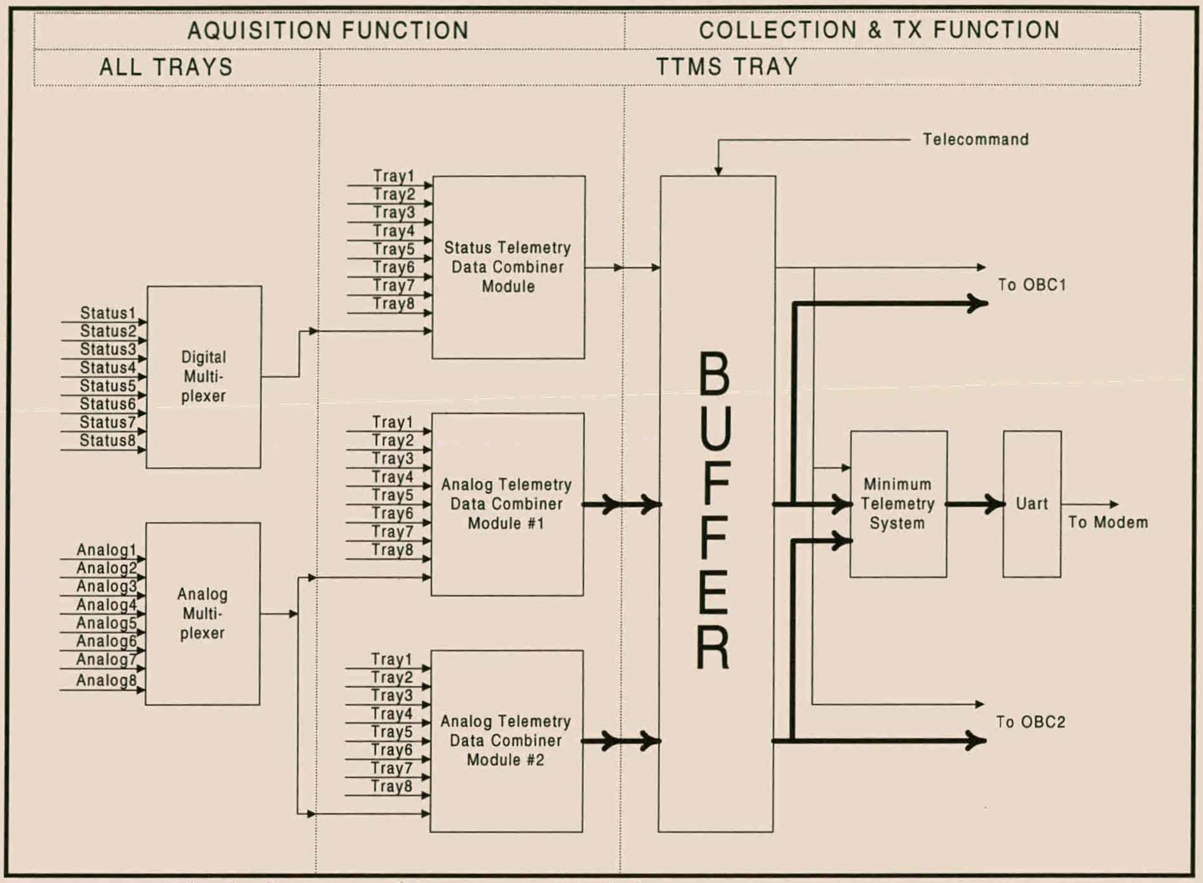

Figure 3.3 - Block-diagram of Prototype Model

The decentralised implementation is used to minimise the amount of wiring between the satellite's trays while still providing redundancy. The redundancy will improve the reliability of the hardware and by minimising the amount of wiring between trays, the weight of the telemetry system is kept to a minimum.

The main features of SUNSAT-1R prototype can be summarised as follows:

- Decentralised implementation.

- Provides for the monitoring of 64 analog and 64 status channels that can easily be extended to 256 analog and 256 status channels.
- The design must use either the telemetry microcontroller or one of the OBC's to transmit the telemetry data.
- Parallel redundant data collection paths to increase reliability.
- Status and analog telemetry data are collected separately and the telemetry system can only collect one type of data at a time. [1]

3.6 THE MINIMUM TELEMETRY SYSTEM

SUNSAT-1R implements a hardware based telemetry function that does not rely on any processor to perform the function. The data acquisition hardware described in the previous sections do not implement any processors. On the other hand, the data collection and transmission hardware could best be implemented with one or more processors to satisfy the flexibility requirement of the design.

To comply with the design requirements for a hardware based telemetry function, the Minimum Telemetry System (MTS) was implemented. This system allows the telemetry system to transmit data without the use of any processors. The MTS will act as a backup system and will be used when the on-board processors have failed and during the first few orbits before launch. Therefore it was configured as the default telemetry transmission subsystem, but not the preferred subsystem.

The telemetry system is able to implement various data formats and transmission protocols. The preferred data format is the AX.25 packet format. However, this is a complicated format that will require a large amount of hardware to implement without a processor. Therefore it was decided to use a simpler format and protocol for the transmission of data by the MTS. The protocol chosen was the standard asynchronous protocol with a transmission rate of 1200 baud. It will transmit 11 bits for every data byte collected. These 11 bits are made up of 1 start bit, 8 data bits, an even parity bit and a single stop bit. Figure 3.4 illustrates the format used by the MTS. The data is transmitted LSB first.

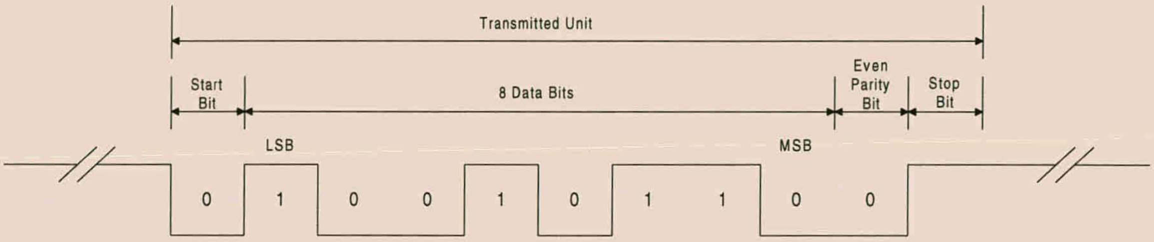

Figure 3.4 - Asynchronous Data Format

The data acquisition subsystem is duplicated for reliability. Each of these two parallel data acquisition subsystems has its own independent MTS. The MTS is implemented using a UART (IM6402 from INTERSIL). The data format used by the UARTs are hardwired and cannot be changed. The UART inputs 8-bit parallel data and converts it to serial data. Figure 3.5 shows a block-diagram of a MTS.

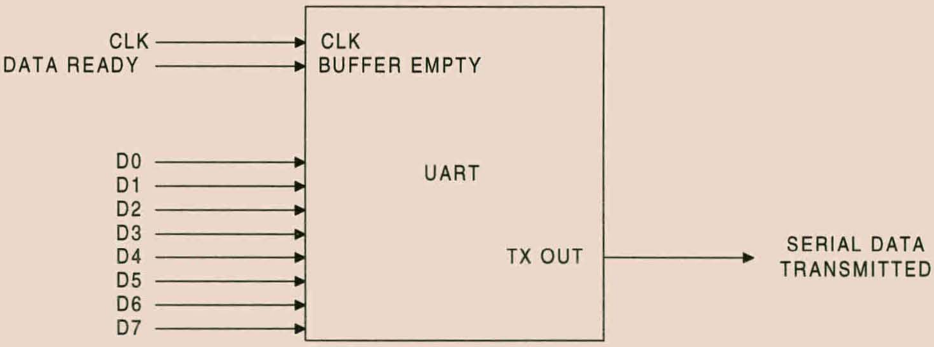

Figure 3.5 - Implementation of a MTS

As mentioned earlier, the MTS will be used as the default telemetry transmission subsystem after launch. System specific software will be needed in the ground station to receive and decode the data received from the MTS.

3.7 THE ON-BOARD COMPUTERS

Part of the telemetry function will be implemented by software on the two on-board computers. The OBC's will be the preferred processors for the collection and transmission of telemetry data. This implies that if the on-board computers are functioning correctly, they will be responsible for the collection and transmission of telemetry data (unless the operator requests data from the telemetry microcontroller). They will implement both the normal collection function as well as the whole orbit data collection function. These processors will perform the telemetry tasks as part of the flight management function.

The data from the three combiner modules (see Figure 3.3) can be input directly by the on-board computers. The OBC responsible for collecting the telemetry data will receive an interrupt, from one of the combiner modules to indicate that valid data is available. Another interrupt generated by the combiner module signals the start of a new frame. [1]

3.7.1 The Telemetry System Microcontroller

The purpose of the telemetry system microcontroller is to act as a backup system to the OBC's for the collection and transmission of telemetry data. The 80C31, 8-bit microcontroller from INTEL was used. If the OBC's should fail, then the microcontroller must collect the telemetry data, convert it to a predetermined format and transmit it using a UART and the AX.25 packet protocol.

The data collection, conversion and transmission will all be under software control. In order to make the system flexible; the microcontroller system was designed to allow the upgrading of the software. New software can be downloaded from the OBC's via the microcontroller's built-in serial port.

Figure 3.6 is a block-diagram of the microcontroller subsystem. The basic boot and controller software will be stored in a 4 Kbyte fusible-link PROM. The contents of this PROM can not be corrupted by the natural radiation in the space environment.

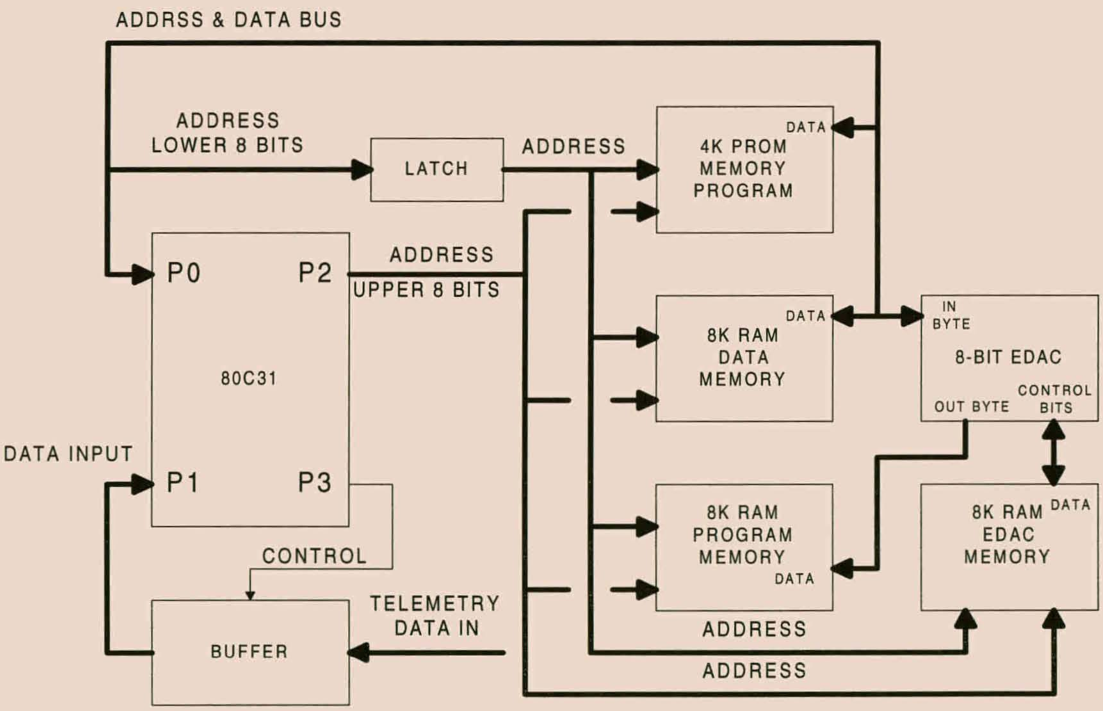

Figure 3.6 - Telemetry Microcontroller System

An 8 Kbyte RAM is provided for the storage of telemetry data and another 8 Kbyte RAM will be used to store new or updated software. To ensure the integrity of the software stored in the RAM, an 8-bit EDAC is implemented. The EDAC is a discrete implementation and requires another 8 Kbyte RAM space for the storage of the error detection information. Although the EDAC takes up a lot of space (it consists of 13 integrated circuits and covers about a third of the total space of the hardware on the TTMS tray), it is essential to ensure that the software being executed is error-free.

The data collection function in the microcontroller is interrupt driven. When the microcontroller receives an interrupt from one of the combiner modules, it inputs the raw telemetry data from that combiner module through port 1. The data is first sent through a buffer that is controlled by the microcontroller. The buffer enables the controller to input data from more than one source.

3.7.2 Data Transmission Hardware

The OBC's and the telemetry microcontroller implement the data transmission function. All three processors use the AX.25 packet format and protocol as the standard format for data transmission.

The AX.25 protocol is a complex protocol that must be implemented in software. (To implement this protocol in hardware would require a tremendous number of components.) Therefore the microcontroller is used as a backup to the OBC's telemetry data collection and transmission function.

The only hardware that is extra to the hardware already described, is the UART, which the microcontroller will use to help with the implementation of the AX.25 protocol. [1]

3.8 SUNSAT 1R – FRAME STRUCTURE

The telemetry system consists of 256 channels, of which the last channel is unused to achieve synchronisation.

The satellite consists of 8 subsystems, viz.:

1) TTMS - Telemetry, Telecommand and Modems
2) P & I (1) - Power & Optics (1)
3) ADCS - Attitude determination and control system
4) RDISK - Ramdisk
5) OBC1 - On board computer 1
6) OBC2 - On board computer 2
7) RF - Radio frequency
8) P & I (2) - Power & Optics (2)

Each subsystem is allocated 32 analog channels. Of these the first 24 channels are 7-bit analog and the remaining 8 channels are 8-bit analog. 24 Status (digital – 1 bit) channels are multiplexed to the first 24 analog channels.

3.9 DATA SYNCHRONISATION

The telemetry system hardware does not transmit channel numbers along with the telemetry data. All the processors used for the collection of telemetry data will have to synchronise a software counter with the received data to keep track of the channel numbers. The hardware provides a means of achieving synchronisation only to the on-board processors. This is in the form of an interrupt signal that indicates the start of a new telemetry frame. The data transmitted by these processors will therefore be synchronised.

However, the Ground Station Control can also receive data transmitted by the minimum telemetry system which has not passed through a processor and which is not synchronised. Since onboard signals are not available in the control station, the data receiving software will have to use an indirect way of synchronising the data. This will not be a problem since the value of known telemetry channels will be fixed prior to launch. Synchronisation can therefore be achieved by comparing successive data frames. The on-board processors can also use this method if the synchronisation interrupt signal fails.

Comparison of Successive Data Frames

The method of achieving synchronisation is a little more complicated and will require more extensive software. However, this is not a problem since this method will usually only be used in the Ground Control Station and other amateur ground stations where available memory will not be a problem. The method will be used by the ground station computers when telemetry data is being received in any format in which the data have not be synchronised by the on-board computer. [1]

4 EVALUATION OF THE EFFECTIVENESS, PERFORMANCE AND INTEGRITY OF SUNSAT'S TELEMETRY SYSTEM

4.1 PRESENT SUNSAT-1R TELEMETRY

4.1.1 Synchronisation of Clocks for Frame Counter

The purpose of the frame counter is to provide time information for each frame so that accurate status of the satellite can be reconstructed at any particular time.

SUNSAT-1R has a 255 byte frame with each byte representing the status of a channel on-board the satellite. A 32-bit counter on each of the two identical systems is incremented by after each frame is generated when the sample speed is set at 800Hz, or incremented by eight if the sample speed is set at 100Hz.

The first four bytes of the frame counter consist of the four bytes of the frame counter. These frame counters were supposed to initialise to zero when the telemetry system is powered up for the first time. A resistor-capacitor circuit connected to the power supply of the telemetry system generates a reset signal connected to the clear-inputs of counter integrated circuits (IC) used (74HC590). However these counters have synchronous resets. The later 3 counters of the 4 cascaded 8-bit counters used will only get a clock signal when the previous counter overflows. By this time, the reset signal is not active anymore and the counters were not reset.

For the future generation satellite, frame counters will not be necessary. The FPGA microcontroller, as proposed in Chapter 5.4 will be able to assign channel numbers to the signals with its built in software.

4.1.2 Masking of Last Byte in Telemetry Frame

The last byte of the telemetry frame, the byte indicating a valid data byte, *INT_TLM*, is suppressed. Instead of the 256th byte being suppressed, the 255th byte is suppressed. This is due to the structure of the 8-bit counter used, the 74HC590, to generate the telemetry channel addresses. The IC has 8 flip-flops implementing the counter, but it also has an 8-bit output register into which the counter value is loaded. Two separate inputs are used to increment the counter and to load the output register, but these are tied together in the SUNSAT-1R implementation. This causes the output of the IC to lag the internal counter value by one. The ripple carry output of the IC, that indicates when the counter has incremented to 255, is used in the circuitry masking out the *INT_TLM* signal. However, because of the lag between the output and the actual count of the IC, the ripple carry output becomes one clock period before the output reaches 255, when it is still 254. This causes the *INT_TLM* signal to be suppressed for the wrong telemetry byte. This will not be necessary for the future telemetry system since telemetry data will not be gathered in this manner.

4.1.3 Power supply

In SUNSAT-1R, each client module is supplied with two power signals from the TTMS module. However, the source of these two power lines are fed from one single track on the pc-board. In the event of a short circuit on the client module, both power supplies will be lost if this single line breaks.

4.1.4 Cable Harness

The TTMS module supplies 12 address lines and 2 power lines to each of the 7 client modules. This high number of cables running throughout the satellite increases the chances of any single line failure, considering the effect of vibration during launch on the soldered connections. Effects of additional weight, space and the effect of the high-speed bus on the cable harness must also be considered.

In the new proposal, it is not necessary for address lines to be supplied to the client modules. The generic FPGA microcontroller on each module will be capable of generating address signals for the desired channels to be selected. All communication between modules will be via serial communication that make the duplication for redundancy feasible.

4.1.5 Protection of Analog Outputs to Buffers / Analog to Digital Converters

There are too many components used to protect the outputs of analog signals to buffers or analog to digital converters. Consideration should be taken to designing circuits within TTL limits so that no protection is necessary.

4.2 EVALUATION OF SUNSAT-1R IN PRESENT ROLE

To evaluate the performance of SUNSAT's telemetry system, inputs are required to stimulate the system and the outputs measured. The present SUNSAT is in space and hence it is not possible to conduct this evaluation. SUNSAT in its present role is a "stand-alone" system. There is only one satellite and one groundstation. This places a lot of limits on the possible functionality of SUNSAT if it were a multi-satellite configuration with multiple groundstations. The following chapters investigate and propose SUNSAT as such systems, discussing their functions and evaluating their performance based on findings found in research articles on similar topics.

4.3 PROPOSAL AND INVESTIGATION OF OTHER ROLES FOR SUNSAT

4.3.1 Performance of SUNSAT as a Two-Layer Satellite Communication Network

4.3.1.1 Introduction

Currently SUNSAT is a "stand-alone satellite". For the future generation of SUNSAT, it is investigated and proposed to construct a "Two-Layer SUNSAT LEO Satellite Communication Network" as shown in Figure 4.1. Such a system can be used for a personal communications system (PCS) or personal communications network (PCN). The investigation and performance analysis of SUNSAT in such a future role is evaluated using an article composed by Jin-Fu Chan, Le-Pond Chin and Chun-Ming Huang, titled "Performance of a Two-Layer LEO Satellite Communication Network".

Mobile communication is attractive in freeing people from trying to a fixed place in order to communicate. In existing cellular mobile communication systems, base stations (BS) handle the traffic within their own coverage while a mobile switching centre (MSC) plays the role as the mobile switch. Geosynchronous satellites can be used to support personal mobile communications, however this is not at all economical because of its strict antenna and power requirement. It is more feasible to use a handset to communicate to LEO satellites.

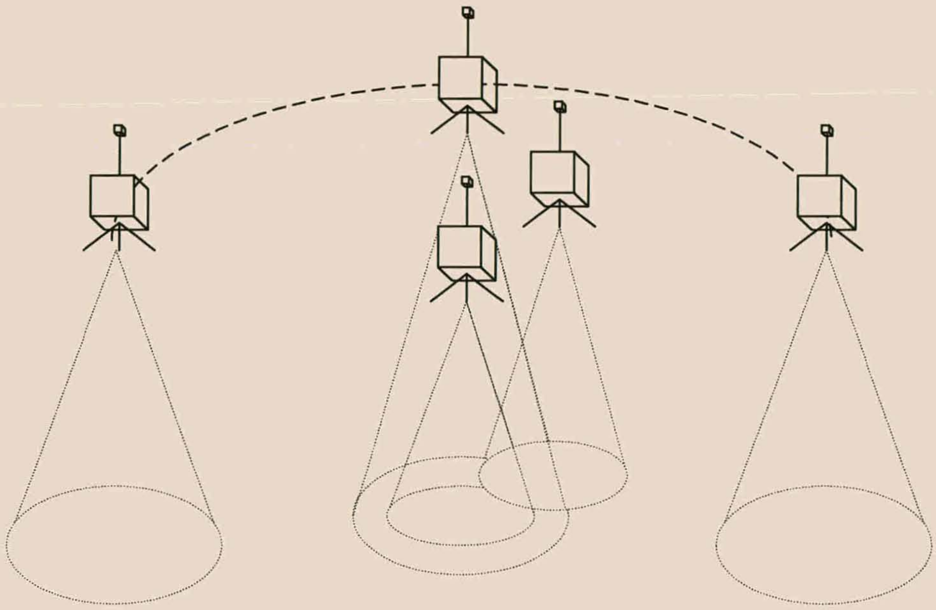

Figure 4.1 - Proposed Future SUNSAT Two-Layer Satellite Network Architecture

A network of multiple SUNSAT LEO satellites has been proposed as a means to support global personal communications (see Figure 4.1). Similar networks which are currently under investigation include Iridium [21], Globalstar [22], Odyssey, Ellipsat, Aries, and etc. [23]. A radiation beam covering a rather large geographical area is called a cell or footprint. Any of these networks can be a stand-alone system and have its own group of subscribers. The distribution of ground traffic is highly variational, for example the traffic in a metropolitan area is denser than in the ocean. People in urban area usually suffer a higher blocking rate.

Intuitively, blocking rate can be reduced by using more satellites or reducing the cell size. To increase the number of satellites is costly. A SUNSAT two-layer LEO satellite network (see Figure 4.1) is proposed to yield lower call blocking rates. The main idea is to add another layer of SUNSAT LEOs at lower altitude to serve more populous areas. In order not to increase the number of satellites, the lower layer is deployed only for regional use, while the altitude of the upper layer is raised to reduce the number of satellites on one hand and to maintain the global coverage on the other hand.

Satellites at the lower layer that service regions of heavy traffic are assumed to be equipped with antennas whose beams can be adjusted to aim at these populous areas. It is further assumed that the channel assignments for these lower satellites are done dynamically in contrast to the upper layer in which fixed channel assignment is normally used.

4.3.1.2 Assumptions and Operation

4.3.1.2.1 Assumptions

1. Each satellite covers equal number of cells and for convenience the number is assumed to be even.
2. Each satellite can perform on-board processing and can communicate with its neighbouring satellites via cross-links.
3. All satellites move in one direction. For example in Iridium, satellites all move longitudinally. From the viewpoint of ground users, these satellites

move from south toward north and then back to south. In this analysis we will call the north-to-south X direction and assume that satellites at both layers all move along the X direction.

4. For convenience, assume that the shape of cells is square and traffic varies in Y direction which is perpendicular to the movement of satellites.
5. Channel time is assumed to be slotted so that the transmission of a packet takes place in one slot.

4.3.1.2.2 Operation

The system operates according to the following rules:

1. Each satellite basically handles calls originated from its coverage. Since all satellites have on-board processors, they also route messages through cross-links.
2. For areas covered by both upper and lower layer satellites, calls are primarily served by the lower layer. Once there is no more channel to accommodate a newly initiated call, the call will be overflowed to the upper layer. If there is still no channel available, the call is then rejected.
3. For areas covered by both layers, the allocated channels must be divided into two disjoint groups to avoid co-channel interference, one for the lower layer and the other for the upper layer.
4. Since lower layer satellites are used to take care of heavy traffic regions, antenna beams are adjusted to aim at the most populous area in the coverage. This can be done by using turnable or adaptive array antennas.
5. Dynamic channel assignment is executed by lower layer satellites so that more channels can be assigned to serve the area of heavy traffic to efficiently reduce call blocking rate. Fixed channel assignment is assumed for the upper

level, i.e., cells covered by an upper layer satellite are given equal number of channels. [19]

4.3.1.3 Analysis

4.3.1.3.1 Notation

L_u Length of an edge of a square cell served by the upper layer satellites

L_l Length of an edge of a square cell served by the lower layer satellites

N_u An integer so that the coverage of an upper layer satellite consists of N_u^2 cells each of which has edge length L_u

N_l An integer so that the coverage of a lower layer satellite consists of N_l^2 cells each of which has edge length L_l

Δd Distance between the centre of coverage and the most populous area served by an upper layer satellite. See Figure 4.2 for the relation among N_u, N_l, L_u, L_l,, and Δd

$\alpha(y)$ Traffic density function under Assumption 4

C_u Number of channels given to upper layer cell

$C_l(n)$ Number of channels available to the n^{th} lower layer cell. Referring to Figure 4.2, 1,-1 is used to denote the two centre cells; therefore the adjacent cells of 1 and –1 are 2 and –2. Numbering of cells in Figure 4.2 is done in this manner

$\alpha_u(m)$ Call arrival rate of the m^{th} upper layer cell

$\alpha_l(n)$ Call arrival rate of the n^{th} lower layer cell

δ Probability that a call will have finished by the end of a time slot

$\beta_l(n)$ Call rejection rate in the n^{th} lower layer cell

$\beta_u(m)$ Call rejection rate in the m^{th} upper layer cell

$\beta_\upsilon(y)$ Call rejection rate at position y

β_υ Maximum call rejection rate of the system

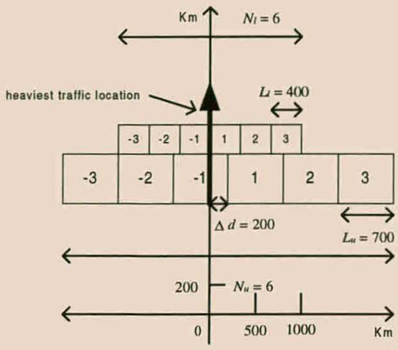

Figure 4.2 - Cell Layout

4.3.1.3.2 Derivation

1. ***Lower Layer Satellites:*** According to Assumptions 1 and 4, the centre coverage of a lower layer satellite falls at the most populous area and the number of cells is even. The blocked calls will be overflowed to the upper layer.
2. ***Upper Layer Satellites:*** For upper layer satellites, the heaviest traffic area may not exactly locate at the centre of coverage. In Figure 4.2, Δd was used to denote the distance between the centre of coverage and the most populous region.

Case 1: Cell m of the upper layer satellite is completely covered by some number of lower layer satellites. Consequently, arrivals are overflowed from the lower layer.

Case 2: Only part of cell m is covered by lower layer satellites.

Case 3: The cells are not covered by any lower layer satellites. Users in these areas are served directly by the upper layer satellites.

Case 4: Cell m is completely covered by some number of lower layer satellites. Thus arrivals are overflowed from the lower layer.

The mathematical derivations for the above scenarios can be found in the paper by L Chin, J Chan and C Huang [19]. The findings can be summarised as:

1. The rejection rate in the region covered by satellites at both layers is the product of the rejection rates of both layers.
2. The rejection rate in regions covered only by the upper layer is simply the rejection rate of the upper layer.

4.3.1.4 Numerical Examples and Discussion

Assuming $\alpha(y) = \alpha e^{-k|y|}$ for traffic distribution, where α is used to denote the peak traffic and k is the decay parameter. For instance, $k = 0.0138$ means that traffic reduces to half of the peak when y = 50. In this example it is assumed that each upper and lower satellite serves 6 X 6 cells, so that the relation between the cell edge length and the number of satellites are given in Table 4.1.

Table 4.1 – Relation Between Cell Edge Length and Required Number of Satellites

Cell Edge Length	No. of Satellites in each Orbital Plane	Number of Orbit Planes	Total No. of Satellites
420	16	8	128
480	14	7	98
560	12	6	72
670	10	5	50
840	8	4	32

Consider a two-layer satellite network with L_u = 820 and the two regional lower layers with L_l = 420. The total number of necessary satellites is 32 + 16 X 2 = 64.

The other parameters are chosen as follows: each unit of time is 1ms and $\delta = 10^{-5}$, i.e., mean call holding time is 100s. From the results obtained by L Chin, J Chan and C Huang, not only is the rejection rate reduced from 20% to 4%, but also the necessary number of satellites from 72 to 64. However, if dynamic channel assignment cannot be exercised, then the performance of the two-layer system may be worse because of the fewer number of satellites used in the system. Thus dynamic frequency assignment is a mandate in the two-layer network [19].

Further investigations proved that by enlarging the cell size decreases the number of satellites, but increases rejection rate. Increasing the number of lower layer satellites reduces the blocking rate. It was also observed that raising the altitude of the upper layer satellite did not severely worsen the performance, but dramatically reduced the number of satellites. The change of coverage for a global satellite system is very difficult to deal with. If not handled accurately, the performance rapidly deteriorates. Accurate adjustment is very costly. It is more feasible for a regional system to adjust its coverage. Therefore the effect of inaccuracy is lessened by using the two-layer satellite network [19].

4.3.2 Performance Analysis and Simulation Study for SUNSAT as a Variable-Channel-Per-Burst SS-TDMA with Multiple Groundstations

4.3.2.1 Introduction

Currently SUNSAT is "stand-alone satellite" with a single groundstation at Stellenbosch University. For the future generation of SUNSAT, it is investigated and proposed to have multiple groundstations within SUNSAT's footprint so that many institutions / organisations can have access to SUNSAT's services at the same time (see Figure 4.3 below).

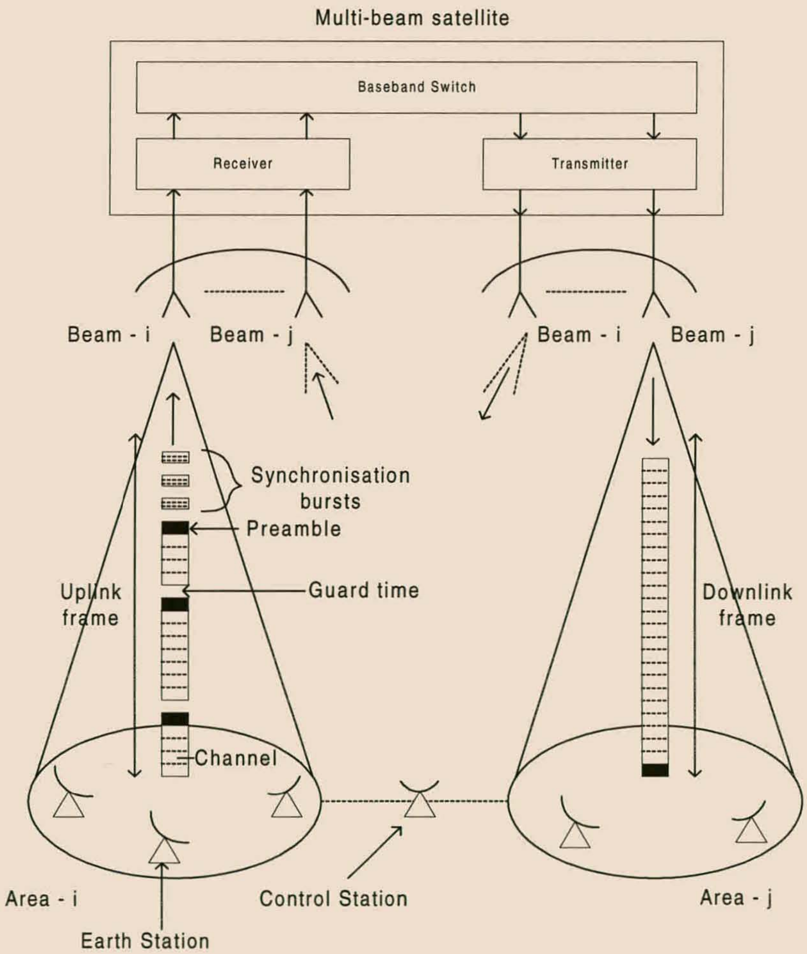

Figure 4.3 - Proposed Future SUNSAT SS-TDMA System With Onboard Baseband Switch

As digital radio communication technologies have rapidly improved, the time division multiple access (TDMA) scheme has played an increasingly important role in diversified radio communication systems, such as satellite communication systems, terrestrial radio communication systems and mobile communication systems. Extensive research and development has been carried out on satellite-switched (SS-) TDMA systems to realise effective frequency use, increase satellite capacity and minimise earth station costs [24] – [27]. This chapter investigates the traffic performance analysis of the future proposed SUNSAT SS-TDMA system with onboard baseband switch and multiple groundstations. An article composed by Masami Yabusaki and Shigefusa Suzuki, titled "Approximate performance analysis and simulation study for variable-channel-per-burst SS-TDMA" is used as a guide for this investigation and performance analysis of SUNSAT in such a future role.

The proposed SS-TDMA with multiple groundstations is shown in Figure 4.3. On uplinks, earth stations transmit synchronisation bursts and traffic bursts to a satellite. At the beginning of a burst, a preamble is inserted for synchronisation and identification. A guard time is inserted between bursts to prevent them from colliding. In the satellite, the receiver extracts the synchronisation bursts and preambles, and then forwards the remaining call data to the baseband switch (BBSW). Each earth station receives a single traffic burst and picks up call data in the designated channels. A unique control station centrally administers channel assignment.

Channels in a frame are separated by bursts. If a call originates from an earth station whose burst has insufficient idle channels, even if there are no idle channels in a frame, the call cannot be assigned channels. However any idle channel in a frame can be shared among all earth stations by reconfiguring the bursts, that is by changing the number of channels in each burst on a call-by call basis (Figure 4.4(b)).

Following, reconfiguration strategies are discussed and traffic performance is analysed from the standpoint of reconfiguration probability and channel utilisation efficiency.

Reconfiguration probability is defined as the ratio of the number of calls connected by reconfiguration to the total number of calls. In large-scaled SS-TDMA systems, the reconfiguration process delays deteriorates channel utilization efficiency because channels are assigned only after reconfiguration is completed. Therefore, a reconfiguration strategy which reduces the reconfiguration probability is required [20].

4.3.2.2 VCPB Advantageous Traffic Domain

Traffic performance of the SS-TDMA system is determined by performance on the uplink and downlink and in the BBSW. Uplink traffic performance depends on channel assignment schemes. Downlink traffic performance is independent of channel assignment schemes. Thus, on the downlink, any channel can be assigned arbitrarily. Traffic performance in the BBSW is also independent of the channel assignment schemes.

The uplink channel assignment schemes are associated with the uplink burst configurations. The simplest conventional configuration available for the SS-TDMA system is single-channel-per-burst (SCPB) as shown in Figure 4.4(a). In the SCPB, calls of each earth station are assigned the required number of bursts on demand. A preamble and guard time pair is required for each burst. In the

VCPB, bursts are assigned to each earth station one-by-one in advance as shown in Figure 4.4(b).

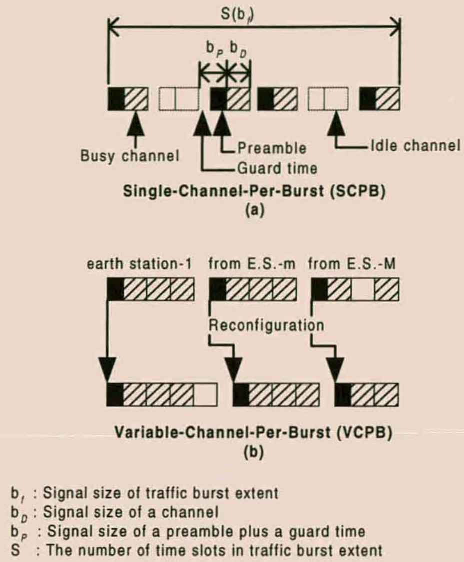

Figure 4.4 - Burst Configurations

Calls of each earth station are assigned the required number of idle channels in its burst on demand. If the number of idle channels in the burst is less than the number required for the call, idle channels are transferred from other bursts (reconfiguration). Any idle channels in a frame can be shared among all earth stations in both the SCPB and VCPB. The SCPB channel capacity is given by:

$$S_s = \quad b_f \,/\, (b_D + b_P) = b_D S \,/\, (b_D + b_P) \qquad (1)$$

where x represents the maximum integer less than or equal to x. b_f , b_D and b_P are the signal sizes [bits] for the traffic burst extent in a frame, one time slot, and one overhead (a preamble plus a guard time), respectively as shown in Figure 4.4. S is the number of time slots in the traffic burst extent. Each signal size is obtained by dividing each time by the TDMA transmission bit rate [20].

The VCPB channel capacity S_v decreases as the number of earth stations increases. It is given by:

$$S_v = (b_f - b_P M) / b_D = S - (b_P / b_D) M \quad (2)$$

Where M is the number of earth stations.

If $$M < b_D S / (b_D + b_P) \quad (3)$$

then

$$S_v > S_{S.} \quad (4)$$

Therefore, from the view of channel capacity, VCPB is advantageous within the traffic domain given by formula (3). For example, for $S = 600$ and $b_D = b_P$, VCPB is advantageous in the domain where the number of earth station M is less than 300.

4.3.2.3 Reconfiguration Process

In the VCPB, reconfiguration must be executed without interrupting calls in progress. The system function required for reconfiguration is shown in Figure 4.5. When a call originates from an earth station in a beam-n and the number of idle channels in the burst of the earth station is less than the number of channels required for the call, reconfiguration is processed in the following order. [20]

4.3.2.3.1 Reconfiguration Planning in a Control Station

Time slot positions at the beginning of each burst, the number of channels in each burst, and time slot positions of the busy channels are replanned at the control station.

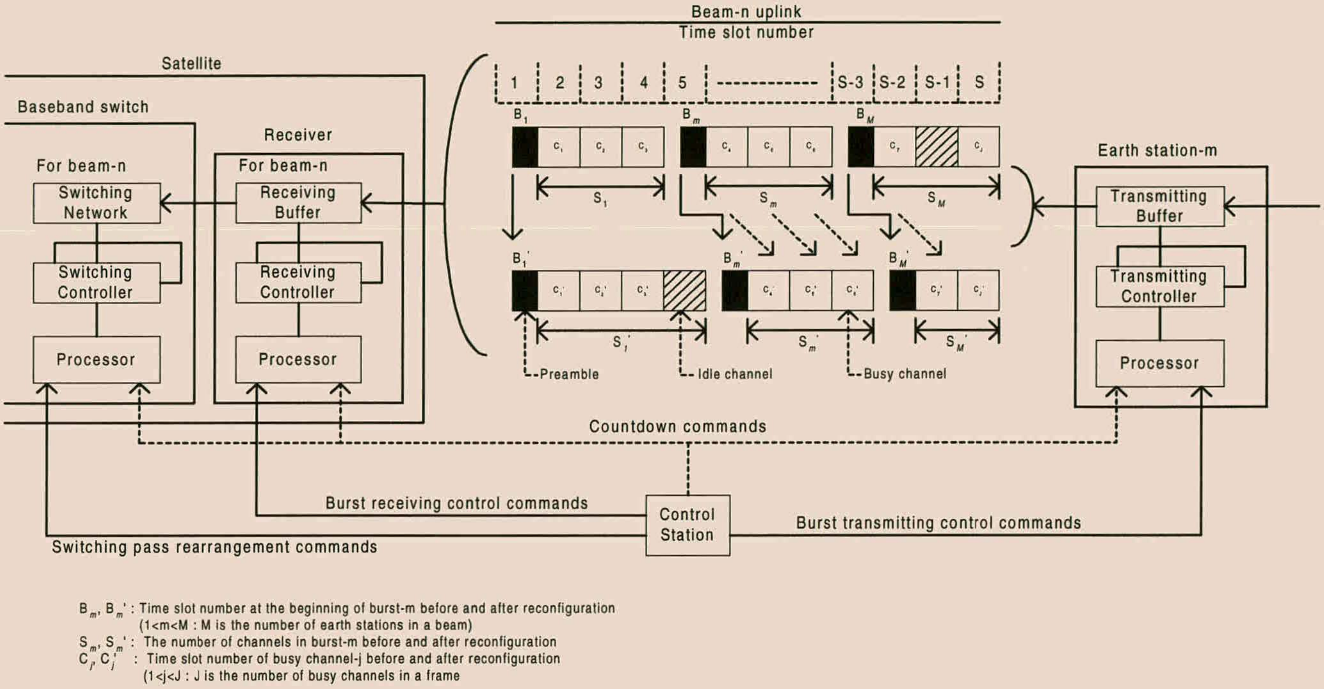

Figure 4.5 - System Function Required for Reconfiguration

Then, reconfiguration commands containing the following information are formatted:

1. n : beam number
2. Bm, Bm' : time slot number at the beginning of burst-m before and after reconfiguration $(1 \le m \le M)$
3. Sm, Sm' : the number of channels in burst-m before and after reconfiguration $(1 \le m \le M)$

4. Cj, Cj' : time slot number of busy channel-*j* before and after reconfiguration ($1 \le j \le J$: *J* is the number of busy channels in a frame of beam-*n*)

4.3.2.3.2 Reconfiguration Command Transmission

The following reconfiguration commands are transmitted to the satellite (receiver and BBSW) and each earth station whose burst needs to be reconfigured.

For satellite receiver: *n*, together with each (B*m*, B*m*') and (S*m*, S*m*')

For BBSW: *n*, together with each (C*j*, C*j*').

For earth station-*m*: (B*m*, B*m*'), (S*m*, S*m*'), together with each (C*j*, C*j*') in burst-*m*.

4.3.2.3.3 Processing in Satellite and Earth Stations

In the satellite receiver, BBSW and earth stations, the reconfiguration commands are recovered. Then, the following control data are distributed to each stand-by controller.

In satellite receiver: burst receiving control data.

In BBSW: switching control data.

In earth stations: burst transmitting control data.

4.3.2.3.4 Reconfiguration Execution

Countdown commands are transmitted to the receiver, BBSW and earth stations to inform them of the reconfiguration execution time. Reconfiguration is executed by simultaneously changing the controllers in the receiver, BBSW and earth stations.

4.3.2.4 Reconfiguration Strategies

In the VCPB, the reconfiguration-process load depends on the reconfiguration strategy. The increase in reconfiguration-process reconfiguration frequency, the number of idle channels in the bursts must be balanced. Thus, the following two reconfiguration strategies, random selection and reallotment are introduced.

[Strategy 1] Random Selection: Idle channels are transferred from other bursts to the burst having insufficient idle channels. These donor bursts are randomly selected.

[Strategy 2] Reallotment: The required numbers of idle channels are reallotted to the burst having insufficient idle channels. The remaining idle channels are reallotted to each burst in proportion to the offered traffic intensity to each earth station.

The third strategy is introduced to narrow the reconfigured burst extent in a frame.

[Strategy 3] Nearest Selection: Idle channels are transferred from other bursts to the burst having insufficient idle channels. These donor bursts are selected from the nearest burst, namely, the burst preceding or succeeding the burst having insufficient idle channels [20].

4.3.2.5 Performance Analysis

4.3.2.5.1 Traffic Model – Channel Assignment Algorithm

To compare the traffic performance using the reconfiguration strategies, the uplink is focused upon. Blockings in the BBSW and on the downlink are not considered to simplify the analysis. The channel assignment algorithm is show below in Figure 4.6.

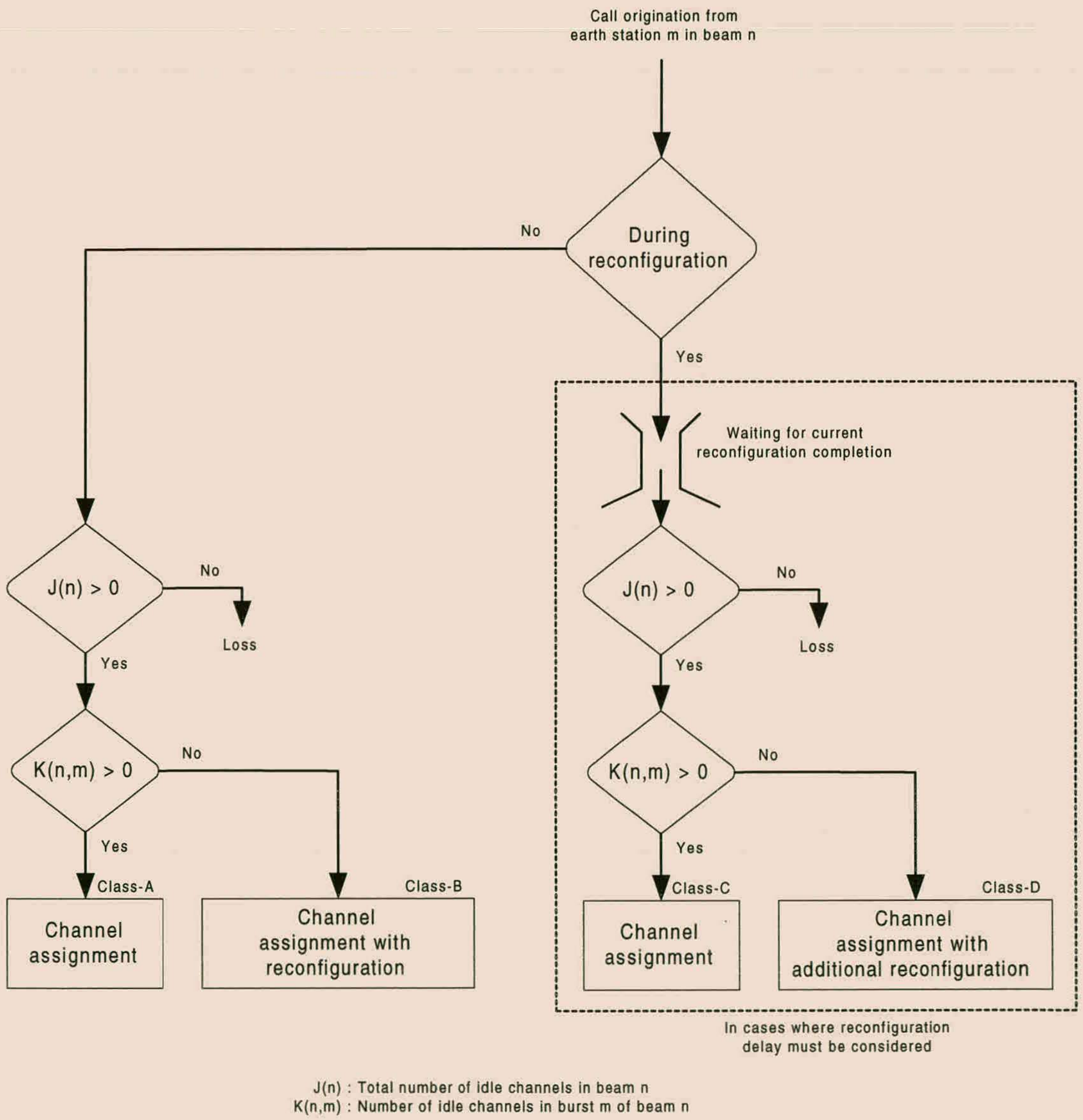

Figure 4.6 - Channel Assignment Algorithm

There are four call classes to be connected in the VCPB:

Class-A: calls which are assigned channels immediately without reconfiguration.
Class-B: calls which are assigned channels with reconfiguration.
Class-C: calls which originate during the reconfiguration process and are assigned channels without additional reconfiguration.
Class-D: calls which originate during the reconfiguration process and are assigned channels with a single additional reconfiguration.

The following parameters were in the simulation:

1. The number of time slots in the traffic burst extent, $S = 600$.

This parameter is based on the system parameters assuming a channel bit rate of 64 kbits/s and a TDMA transmission bit rate of 40 Mbits/s.

2. An overhead signal size b_P = a channel signal size b_D (=192 bits)

This parameter is based on the system parameters assuming a channel bit rate of 64 kbits/s and a TDMA frame length of 3ms.

2. Loss probability $B_0 = 0.01$.
3. Mean holding time = 180s.

Simulation experiments were run using the FORTRAN-77 simulation language. The total number of originating calls in each run was 100 thousand. To obtain statistics on calls in the equilibrium state, the statistics were cleared after about 30 thousand calls had been generated. Each experiment was repeated ten times using a random number generator. 95% confidence intervals were computed by the batch means method [20].

4.3.2.6 Reconfiguration Probability

Reconfiguration probability is defined as the measure of reconfiguration frequency:

$$\text{Reconfig. probability} = \frac{The..number..of..calls..connected..by..reconfiguration}{The..total..number..of..calls}$$

The number of channels in each burst transits differently depending on the reconfiguration strategy. State transition of the number of channels in each burst correlates with the state transition of the number of calls in each burst. It is too difficult to strictly analyse the configuration probability taking into consideration this correlation of each reconfiguration strategy. Therefore approximate analysis for the reconfiguration probability is attempted. It is assumed that the reconfiguration process delay is negligible [20].

From the analysis conducted by M. Yabusaki and S. Suzuki, the reconfiguration probability is approximated by the incomplete loss probability fixed-channel-per-burst (FCPB) configuration, weighted by the distribution probability of the number of channels in a burst. The distribution is close to the binomial distribution regardless of the reconfiguration strategy. Reallotment makes the reconfiguration probability lower than other reconfiguration strategies. The reconfiguration probability with reallotment becomes as low as the approximated value , as the number of earth stations decreases. This means that reallotment makes it possible to let the state transition of the number of channels in each burst be almost independent of the state transition of the number of calls in each burst. Moreover, considering the reconfiguration process delay, reallotment also improves channel utilisation efficiency as a result of reducing the reconfiguration probability [20].

4.4 Proposal and Investigation of systems for Evaluation of SUNSAT

4.4.1 Proposal and Investigation of Integrity Checking System for SUNSAT

4.4.1.1 Introduction

SUNSAT is a real-time system (RTS) where the validity of results produced by the RTS depend on both logical correctness and timeliness. The correctness of real-time system depends not only on logging the results produced, but also the clock times when results were produced. The satellite controller relies on a real-time database (RTDB) to log satellite telemetry useful in carrying out its control functions. A RTDB is a collection of data items needed for instantaneous control, operator display, alarm monitoring, and other RTS applications and which are validated by the passage of real-time. This chapter introduces the fundamental features of the proposed integrity checking system for SUNSAT in terms of a collection of communicating processes.

The integrity of satellite telemetry is defined in terms of relevance, correctness, completeness and confidence. The relevance factor provides the basis for partitioning the telemetry data set into relevant and irrelevant data for current processing needs. This in turn enables a satellite monitoring system to vary the amount of data according to the load on the system. The correctness factor deals with the accuracy as well as the timeliness of telemetry data. The completeness factor in accessing the integrity of telemetry data makes it possible to choose a representative set of available data for analysis. This factor takes precedence over the relevance factor whenever a satellite exhibits anomalous behaviour such as uncontrollable spin, or component failures. The confidence factor determines the data-sampling rate. The contribution of this chapter is the proposal and investigation of a complete integrity checking system for SUNSAT's telemetry.

4.4.1.2 Integrity Checker for SUNSAT's Subsystems

Figure 4.7 below illustrates the proposed architecture for the future generation of SUNSAT.

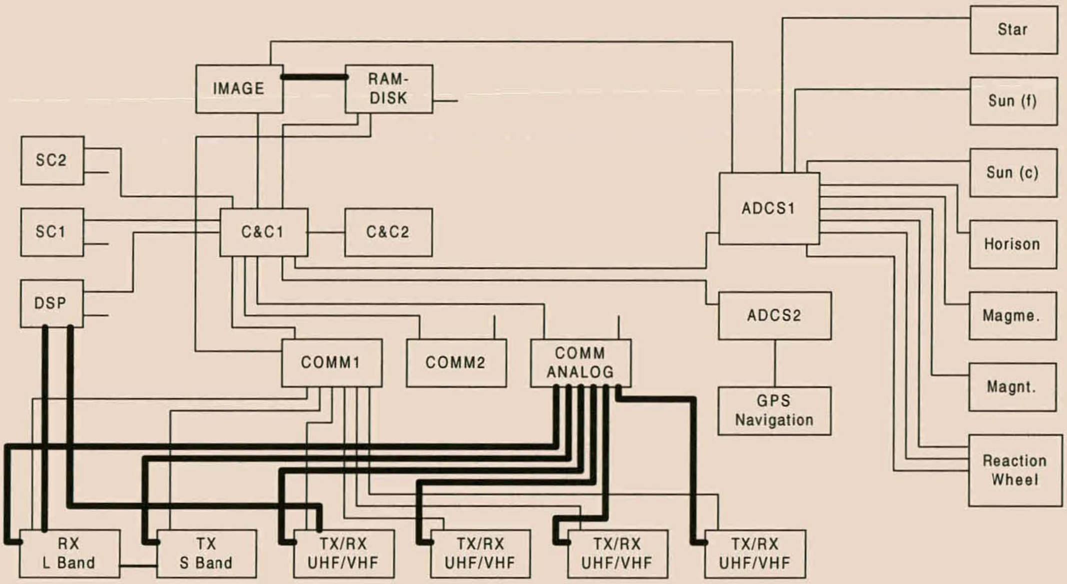

Figure 4.7 – Proposed Future Generation SUNSAT Architecture

Telemetry from all the illustrated subsystems are sent to the two main onboard command and control computers C&C1 and C&C2. Data is processed onboard the satellite for the daily functioning of the satellite.

4.4.1.2.1 Integrity Checking System

Telemetry data is transmitted to the groundstation via one of the satellites communication links. The integrity-checker-centred communicating processes relative to C&C1 and C&C2 relative to Figure 4.7 are shown in Figure 4.8. Each subsystem in Figure 4.7 has an associated process in Figure 4.8.

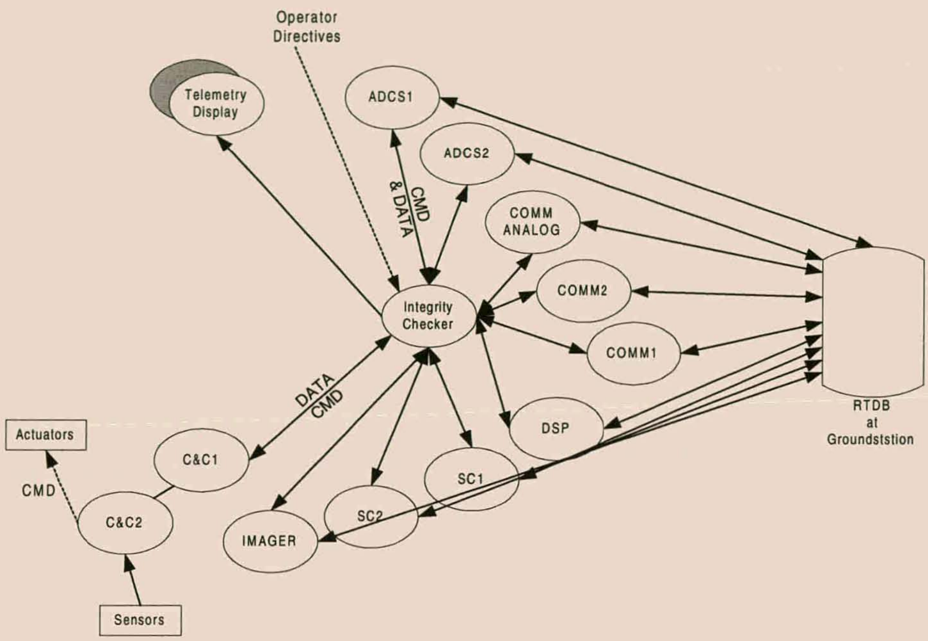

Figure 4.8 – Integrity-Checker-Centred Processes for SUNSAT Groundstation

4.4.1.2.2 Integrity System Database

Each item of a RTDB is a set of (attribute, value) pairs such that:

data item = { (attribute, value) | attribute: string; value: domain }

The first pair (attribute, value) in the set serves as a key (or criterion) in identifying a data item. The term domain specifies a pool of values from which an attribute derives its value [28].

Let $x \in$ RTDB, (A_x, A_x'value) $\in x$, where A_x is an attribute of data item x and A_x'value is the value of the attribute. Let T_{A_x} (point of observation) be the reading of the external clock when (A_x, A_x'value) is first entered into the RTDB;

let k be the number of ticks (beyond T_{A_x}) during which (A_x, A_x'value) is valid. Then $T_{A_x} + k$ (point of validity) is the upper limit on the validity of the information which (A_x, A_x'value) represents. Let q.time (t_use) be the time in state q in SUNSAT's control system when (A_x, A_x'value) is used. Then a *current observation* is one which is made at time t_use where $T_{A_x} < t\_use < T_{A_x} + k$. Each process in Figure 4.8 has a stored value for a set of attributes in the table (name, value, time, *r*_factor, *c*_factor, range_constraints, time_constraints, other_constraints). For example, the *r*_factor range from 0 (irrelevant at the current time) to 3 (most relevant at the current time). A sample table entry for the database in Figure 4.8 would have the following form:

(TR-A, on, 10:05 A.M., 3, 10 seconds, (on, off), $0 \le$ hours ≤ 10000). The correctness criteria are expressed in terms of various constraints. The attributes that can be changed by an Operator Directive are *r*_factor, *c*_factor and any constraint. A process only stores the current value for each attribute [28].

4.4.2 Proposal and Investigation of a Software Package for the Performance Evaluation of SUNSAT with Adaptative Allocation of Onboard Common Resources

4.4.2.1 Introduction

For the future proposed multi-SUNSAT (Two-Layer) configuration (Chapter 4.3.1), simultaneously operating to a large number of widely spread groundstations (Chapter 4.3.2), the use of onboard common resources is envisaged to be shared among those stations undergoing severe fading conditions caused by rain attenuation [30]. The main factor limiting the effectiveness of such techniques is the spatial correlation of the rain across distances of some hundreds of kilometers (regional systems), expressed in terms of probability that the "help" is simultaneously requested by several stations.

Stellenbosh, where SUNSAT's current groundstation is, is well known for heavy rainfall during winter. Similarly, with SUNSAT's future proposed multi-satellite, multi-groundstation configuration, this software would be useful for regions that have high rainfall during some part of the year. On the basis of extensive measurements and of detailed studies carried out on this subject in Italy, for a high number of locations and a statistically significant period [31], a model has been developed for assessment of the above mentioned probability, starting from readily available rain data and from suitable functions expressing the space decorrelation of rain, assumed of general validity. The model has been implemented in a ready-to-use software package which can be applied to any actual configuration and furnishes straightforward indications about the performance about the system [29].

4.4.2.2 System Parameters

The "dynamic onboard allocation" philosophy consists of an extra resource, realisable in many possible ways, which can be temporarily allocated by SUNSAT to the groundstations in severe propagation conditions. Outage happens whenever the number of requests for help is higher than the number of extra-resources available. Taking into consideration the general case of a system which can simultaneously assist M stations out of a total of N, two probabilities are of interest [32]: the *"probability of overrequest"* P_{ovr} which impacts the system as a whole: overrequest occurs whenever more than M stations ask for "help"; the *"probability of not being helped"* $P_{nbh,}$ which regards each station individually. In this latter case two different situations can be envisaged: when no hierarchy applies among the stations (P'_{nbh} for any station) and the resource is assigned on a "first come – first served" basis, and when a hierarchy is assigned to the stations for servicing resource requests (P''_{nbh} for the station with the lowest priority) [29].

The statistical process of joint rain attenuation (rain rate) in groups of sites has been approached under the basic hypothesis that the joint probability of rain attenuation (rain rate) is log-normal provided that attenuation exceeds zero simultaneously in all the considered sites [31].

4.4.2.3 The software package

The package (LASCA) calculates the outage probabilities for both the onboard system and for each station, using very readily available input data. For each station, the programme requires the geographical coordinates (latitude, longitude and altitude), the fade margin and the cumulative distribution of the attenuation. When this latest information is not available the programme can calculate it from the attenuation value exceeded for the 0.01% of the year or directly from the rain data (rain rate exceeded for the 0.01% of the year). The output of the programme furnishes the outage probabilities, both in terms of year percentage and of the corresponding duration (minutes / year) for the common resource system as a whole (P_{ovr}) and for the individual stations (P_{nbh}). For these latters the fade margin, the probability of outage in case of no common-resource facility and the probability of not being helped, in the two cases when no hierarchy applies and when the lowest priority is assigned to the station, are given allowing the evaluation of the improvement introduced by the common resource system [29].

5 PROPOSALS

5.1 AN FPGA-BASED APPROACH TO THE COMPACTING OF THE SUNSAT-1R TTM SYSTEM

In his thesis "An FPGA-based Approach to the Compacting of the SUNSAT-1 TTM System", October 1998, A.G. le Roux proposes to fit two systems (Telemetry and Modems; and the Telecommand system) on one tray, thereby reducing crucial commodities on the spacecraft, viz. weight and space (in SUNSAT-1R, each system occupied a single tray). All the functions of SUNSAT-1R were maintained in the proposal, with the digital functions being implemented with FPGA configurations and the analog functions remained as they were.

SUNSAT-1R has two identical minimum telemetry systems that are hardware based (using the Intesil IM 6402 UART) and one software base telemetry system, using the 80C31 microcontroller. This entire design was duplicated in his proposal, with the two duplicate systems being clocked by a single crystal. If the crystal fails to function for some reason, the duplicate system is of no advantage.

The author of this thesis disagrees with this total functional copy of SUNSAT-1R using FPGAs to replace the digital functions. The strongest reason for this motivation is that the cable harness is not minimised. There are 12 address lines connected from the TTMS tray to the 7 client trays and 3 signal lines from the client trays back to the TTMS tray.

Additionally, there is no reason to keep the telemetry architectural design of SUNSAT-2R identical to that of SUNSAT-1R. Use of microcontrollers can replace many functions of digital logic as can be seen in the proposal in Chapter 5.4.

It is proposed the entire system architecture of SUNSAT be reviewed. The proposal of S. Mostert, "SUNSAT-2R: Mission Analysis, Resources and Architecture" is investigated and taken further in this proposal.

5.2 PROPOSED SUNSAT-2R SYSTEM ARCHITECTURE

The SUNSAT-2R proposed system architecture is based upon the advantages of mechanically separate building blocks with as much as possible autonomy of control within each building block. Figure 5.1 shows the complete satellite in the new architecture (note that all communication links are not shown for the second Command and Control (C&C) processor).

The architecture consists of generic building blocks that are interconnected in star like networks. Each building block has its own intelligence and forms an integral part of one function, for example the reaction wheel below in Figure 5.1.

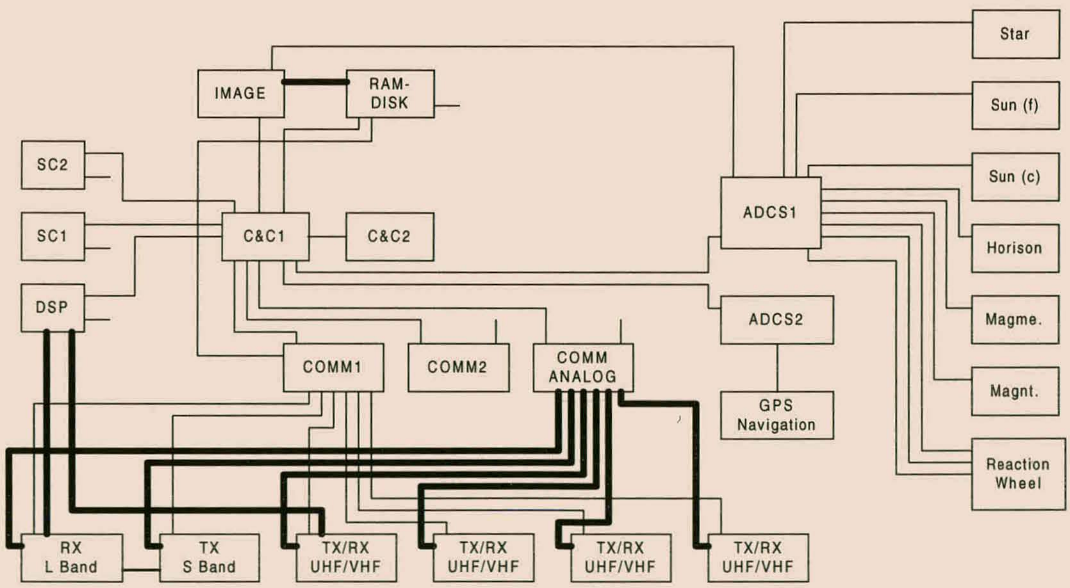

Figure 5.1 - Complete SUNSAT 2R Architecture

Architecture of Generic Component

Each building block as seen in Figure 5.2 is responsible to collect its own telemetry and actuate its own telecommand. Each building block has at least two identical serial ports over which commands are received and replies sent.

Each building block has a standard interface that consists of the two serial channels and any application specific port, i.e. high-speed audio or antenna port. All building blocks support the same protocol over their serial links that can be extended according to the specific function that the block performs. [2]

The generic building block consists of a processor which has included with it on the same package: EPROM, RAM, analog to digital converters, digital to analog converters, timers, two serial ports and FPGA logic. The program is stored in the EPROM and the RAM is accessible with no hardware EDAC. If secure data is required, the EDAC is performed in software.

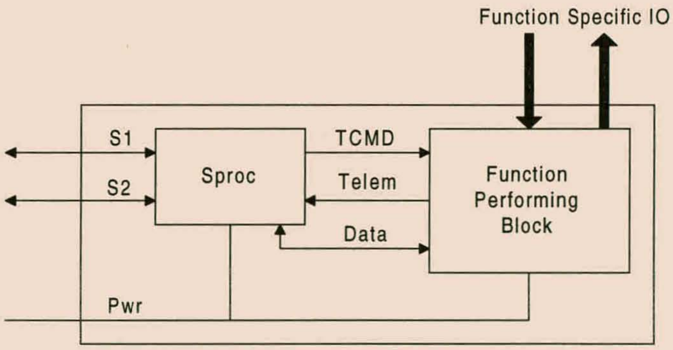

Figure 5.2 - Generic Building Block Architecture

5.3 USE OF FPGAS

The Field Programmable Gate Array or FPGA as it is more widely called is a type of programmable device. Programmable devices are a class of general-purpose chips that can be configured for a wide variety of applications.

5.3.1 Choice of FPGA

A variety of FPGAs are available on the market. Gerhard le Roux, in his research to compact the TTMS system into FPGAs has investigated a few of these technologies, specifying why some are more desirable than others. His findings are detailed below. Additionally, some of the effects of harsh space environment are discussed and the influence of these on semiconductors.

5.3.2 What are FPGAs?

FPGAs supply the three elements sought by digital designers, viz. storage elements (latches and flip-flops), logic and wires [6]. Storage elements can hold states and store data. Logic can perform certain operations on inputs such as Boolean algebra. The wires enable communication between the logic and storage elements. These elements enable the designer to make an application-specific circuit. FPGAs provide a blend of standard parts (AND-gates, flip-flop packages, etc.) and traditional application-specific integrated circuit (ASIC) solutions, but at a lower cost [3].

5.3.3 Design Entry Method

Various methods are available to enter a design for FPGA implementation. With the schematic capture method, the schematics of the design are drawn with a suitable schematic tool and then a netlist of the design is created. This netlist is passed onto the FPGA software for compiling, placement and routing. Theses processes break up the design, assign logic functions to logic blocks (placement), after which the routing between logic blocks is executed.

The design entry method possible is VHDL (Hardware descriptive language) using VHSIC (Very high-speed integrated circuit). Using VHDL, the design can be technology independent thereby allowing the code to be targeted to various architecture types and devices [3].

5.3.4 Radiation Hazard

This section details the radiation environment of earth orbits and some of the effects of radiation on ICs [10]. These effects are important to consider when choosing an FPGA technology.

The sun emits a stream of electrons and protons because of the continuous nuclear fusion within it. This is also known as the solar wind, radiating in all directions from the sun. A much lower number of electrons and protons are also present in the background due to radiation from the stars. Also, high-energy protons and heavy ions from origins such as novas and supernovas are present. All these particles make up the total radiation experienced in interplanetary space. Near planets and stars, however, some particles are trapped and others deflected due to strong magnetic fields. Some of these particles are concentrated in belts around a planet, such as the Van Allen belts surrounding the earth. The radiation encountered by a spacecraft therefore is highly dependent on its orbit.

The most radiation friendly environment for a spacecraft is in a Low Earth Orbit (LEO, <500 km), with a low inclination (<28°). Dose rates encountered in this orbit range from 100 to 1000 RAD(Si)/year (Radiation Absorbed Dose – Si indicates that this figure is for Silicon). The LEO is shielded by the Van Allen belts, because of the particles being trapped in them. In the densest regions of the Van Allen belts, the dose can be from 100 kRAD to 1 MRAD(Si)/year. Satellites in Geo-synchronous Orbits (GEO) are outside most of the trapped radiation, and receive dosages of about 5 kRAD(Si)/year.

Effects of radiation on ICs include Single-Event Effects (SEEs), and Total Dose (TD) ionization. SEEs are caused by electrons, protons and heavy ions that penetrate the spacecraft and cause ionization in silicon and silicon dioxide layers. This ionization can corrupt a memory cell's content (a Single-Event Upset, or SEU), or cause latchup (Single-Event Latchup, SEL), which may destroy the device. Total Dose is the accumulated ionization of an IC over its lifetime. This degrades the device's performance parameters, and eventually leads to its failure [3].

5.3.5 SRAM versus Anti-Fuse

Most popular FPGAs are reconfigurable. A new configuration can be downloaded to the FPGA at will, changing the routing between logic blocks and the functions of logic blocks. This is achieved by changing the states of the programmable switches inside the FPGA.

The alternative is FPGAs that use anti-fuses to program connections and switches. Once the device is programmed, the configuration cannot be changed. The advantages of reconfigurability are obvious. During development, changes can be made quickly to the design on the FPGA. Even in final application, new configurations can be downloaded to upgrade the design, or remove errors found at that late stage. Anti-fuse do not offer these advantages, but can lead to smaller component count when compared to reconfigurable FPGAs utilizing SRAM cells to program switches. This is because the SRAM based FPGAs lose their configuration when powered down, so it must be uploaded each time the device is turned on. This can be done from an external ROM, EPROM, EEPROM, or even from a microprocessor. The anti-fuse device on the other hand is non-volatile and once configured, it is functional each time the FPGA is turned on. Other FPGAs use on-chip EEPROM cells to store their configuration. A variation on this technique is to load the configuration into SRAM cells (than control configuration switches) from on-chip EEPROM on power-up.

The main disadvantage of SRAM based FPGAs is its configuration cells' susceptibility to SEUs [11]. When ionization changes the state of a configuration switch, the device function might be lost, or worse, an invalid configuration might result, possibly destroying the device [12]. Other problems like bus contention on internal tri-state buses, isolation of pull-up resistors resulting in floating inputs and oscillations, turning input modules into output modules, etc., can also result from SRAM cell SEUs [12]. Although in many cases the configuration can be restored by reconfiguring the device, this might not be acceptable in a critical system, such as the telemetry module of the satellite, where it is important that the system is always functional.

On the other hand, the anti-fuse technology used by Actel, Oxide-Nitride-Oxide (ONO), has a very low probability of failure, as the type of heavy ions needed to induce a failure in an antifuse is very rare [12]. Quick logic also markets anti-fuse FPGAs, but uses an amorphous silicon metal-to-metal (M2M) technology to implement their anti-fuses. These anti-fuses are even more resistant to heavy ion radiation than the ONO type, but the devices themselves have very high susceptibility to SEL [11, 3].

5.3.6 Total Dose Effects on FPGAs

The anti-fuse FPGAs from Actel have a major advantage over other SRAM-based FPGAs because of the anti-fuse's high total dose tolerance [13]. The lack of and unattractiveness of alternate FPGAs has led to a great deal of study of Actel FPGAs [11]. Many devices from Actel have been subjected to total dose, SEU and SEL testing, with varied results. It was shown that the radiation hardness of these devices varies from lot to lot, that devices from different fabrication plants have different hardness, and that feature size (around 1.0 μm) also has an influence. The 1.2 μm and 1.0 μm process A1280A can typically withstand up to 6-7 kRAD(Si). However, TD testing of the newer 0.8 μm and 0.6 μm process A1280XL has shown a capability of 4 kRAD(Si) or less [12]. Also devices from the Chartered Fabrication Plant have inferior radiation performance when compared to devices produced at Matsushita Electric Company, 2.2 kRAD(Si) and 30-50 kRAD(Si), respectively, in the case of an A32140DX [12]) [3].

A1280-series TD Test Results

To date, the largest number of radiation tests of commercial FPGAs has been done on Actel's A1020 and A1280 devices, and some results were very promising. Because of their inherently good radiation properties, these two devices are also manufactured in radiation hardened versions, the RH1020 and RH1280. Results for the commercial A1280, the larger of the two, vary. Many tests irradiate the device until functional failure. However, current levels at this point can be very large, exceeding the operating specification of the device. Depending on the system in which the FPGA is embedded, it is possible that this large current cannot be supplied. Thus, although the device might still be functional, the system cannot keep it in a powered up state, and it might be switched off or a safety fuse will blow, disabling the FPGA. Therefore it is important to keep in mind the power supply of the device when viewing TD results. The A1280XL devices from the Winbond Foundry exhibit poor radiation immunity. An 0.8 µm device failed between 2 and 4 kRAD(Si) with a current increase of 700mA, while a 0.6µm A1280XL device from the same foundry failed at 2.5 kRAD(Si) [12, 13, 14]. The same device from Chartered Semiconductor Manufacturing (CSM) also showed poor performance.

A comparison of devices revealed that devices fabricated at the MEC foundry performed the best. An FPGA like the 1.0 µm A1280A from MEC was tested and survived approximately 6-7 kRAD(Si), with a standby current of less that 6mA [12]. Other tests have shown this device to withstand more than 10 kRAD(Si) [13]. On the other hand, tests by NASA and the Goddard Space Flight Centre (GSFC) in December 1997, on the A1280 from MEC, showed poor results, with devices exceeding 20mA standby current after only 3 kRAD(Si) [17]. Another report also showed poor results, blamed it on improvements made to the charge pump of the A1280A device [11]. This report also showed that the increase in current consumption during irradiation was less when the device was not biased (turned off). Thus, this device will survive longer if it is not turned on during its exposure to radiation [3].

The conclusion that can be made from these widely differing results is that lot-to-lot differences sometimes improve performance, while worsening it at other times [11]. When choosing an Actel commercial FPGA for space use, the best foundry is MEC, because many tests have shown that some lots from there have excellent radiation performance. Care must be taken, though, as lot-to-lot variances are large, and devices should be taken from a lot that was tested for TD susceptibility [3].

5.3.7 SEU and SEL of FPGAs

The danger of SEUs for the configuration cells of SRAM-based FPGAs was already discussed. SEU is also a concern in anti-fuse devices, because data registers can be upset, causing incorrect functioning of the logic. This is usually not dangerous to the device itself, only data gets corrupted. However, depending on the application, data integrity can be crucial. Parts which are hardened to specific total dose radiation levels are not necessarily less sensitive to SEE [15]. Therefore, devices are tested for these effects separately.

SEL is a great danger to semiconductor devices. The excessive power supply current that can be caused by an SEL can destroy the device if the current is not limited, or the power to the device is not reset. In a certain test, bulk CMOS FPGAs, like those from Quicklogic, Atmel, Lucent, GateField and Xilinx showed low latchup thresholds (with the Chip Express QYH580 being an exception). Epitaxial CMOS, like those from Actel, performed much better, although CMOS devices are not necessarily latchup immuned. [3]

SEU and SEL performance of the A1280-series

As with TD testing, the foundry manufacturing the device is a great influence on Actel FPGAs' SEE susceptibility, as does the lot number that the device comes from. The measure for SEE is Linear Energy Transfer (LET) with the unit of *MeV-cm²/mg*. From a summary of the radiation performance of Actel devices, the foundry concluded that devices with a SEL LET of less than 37.5 MeV-cm²/mg are considered not suitable for space applications [16].

The A1280-series devices have two basic logic blocks: the C-Module (for combination logic) and the S-module (for sequential logic). It was seen that flip-flops made from S-modules are very soft, showing SEUs at low LET (3 to 8 MeV-cm²/mg), while the C-modules are relatively hard (LET of 26-28 Mev-cm²/mg). Proton upsets are also a concern for LEO satellites. The A1280XL (0.8µm and 0.6µm technology) showed susceptibility to proton upsets, while the A1280A (1µm) from MEC did not [12, 3].

5.3.8 Conclusion on Choice of FPGA

Considering the information in the previous sections, the conclusion is drawn that if a commercial specification FPGA is to be used, the anti-fuse devices from Actel are the better choice. The A1280A 1µm technology devices from the MEC foundry have demonstrated excellent radiation behaviour, with standby current (Icc) still being in specification limits at up to 10kRAD(Si) (0.0028 RAD(Si)/sec), and immunity to latchup. By avoiding the use of S-modules, the device can be made less susceptible to SEUs.

With the SUNSAT-1R mission having a predicted lifetime of five years, the total accumulated dose it will get is around 12.5 kRAD(Si), or about 2.5 kRAD(Si) per year [18]. Although commercial A1280A devices have remained functional for up to 18 kRAD(Si), their current consumption at these total dose levels would be beyond the abilities of the SUNSAT-1R power system. A more reasonable total dose for this device is around 5 to 10 kRAD(Si). This means that these FPGAs would probably have a useful life of about 3 years (at approximately 2.5 kRAD(Si) per year, a total dose of 7.5 kRAD(Si) would accumulate), at which time they would be staring to consume currents in excess of the power system's capabilities. That is, when the orbit used is the same as SUNSAT-1R, and the devices are in a powered-up state all the time [3].

Radiation hardened versus Commercial parts

Actel offers the A1280-series in a radiation-hardened version, the RH1280, which can withstand up to 300 kRAD(Si) total dose levels. Compared to the commercial version, the RH1280 has a few drawbacks. The larger of these is its price, costing ten times more than is commercial equivalent. This might not be feasible in the amateur satellite industry, which SUNSAT is part of. Recently, many non-amateur spacecraft projects are looking into using commercial, off-the-self (COTS) parts, because of the potential savings [14]. Another drawback is the high maximum current consumption of the radiation–hardened device: 25mA compared to the commercial component's value of 2mA. Also, the SEU rates of the RH1280 device are not significantly better than that of the A1280 [14, 3].

5.4 Proposed FPGA and Microprocessor on One Silicon Chip

Integrating reconfigurable devices with processors is an active area of research for many groups around the world. See Appendix A.

The FPGA and microprocessor on one silicon chip as shown in Figure 5.3 below is proposed for the second generation SUNSAT-2R. Experience in Low Earth Orbit (LEO) has indicated that microprocessors such as the 8031 and H-8 are reliable in use. [2] The microprocessor will have included in the same package, EPROM, RAM, Analog to Digital converters, Digital to Analog converters, timers, 2 serial ports and FPGA logic. The FPGA to be used will be one similar to the commercial A1280 manufactured by Actel. Although this FPGA microprocessor does not exit as yet, active research as detailed in Appendix A holds promise to the advent of such a device in the near future. The design proposed in this chapter is a conceptual system design for the future generation of SUNSAT.

5.4.1 Telemetry Subsystem Hardware

Figure 5.3 is a more detail system description of Figure 5.2, the generic building block architecture. As described earlier in Chapter 5.1, the generic building block will consist of a microprocessor which has included on the same package: EPROM, RAM, analog to digital converters, digital to analog converters, timers, two serial ports and built in FPGA logic. A system level description of the telemetry system function performing block and the FPGA logic configuration is described below.

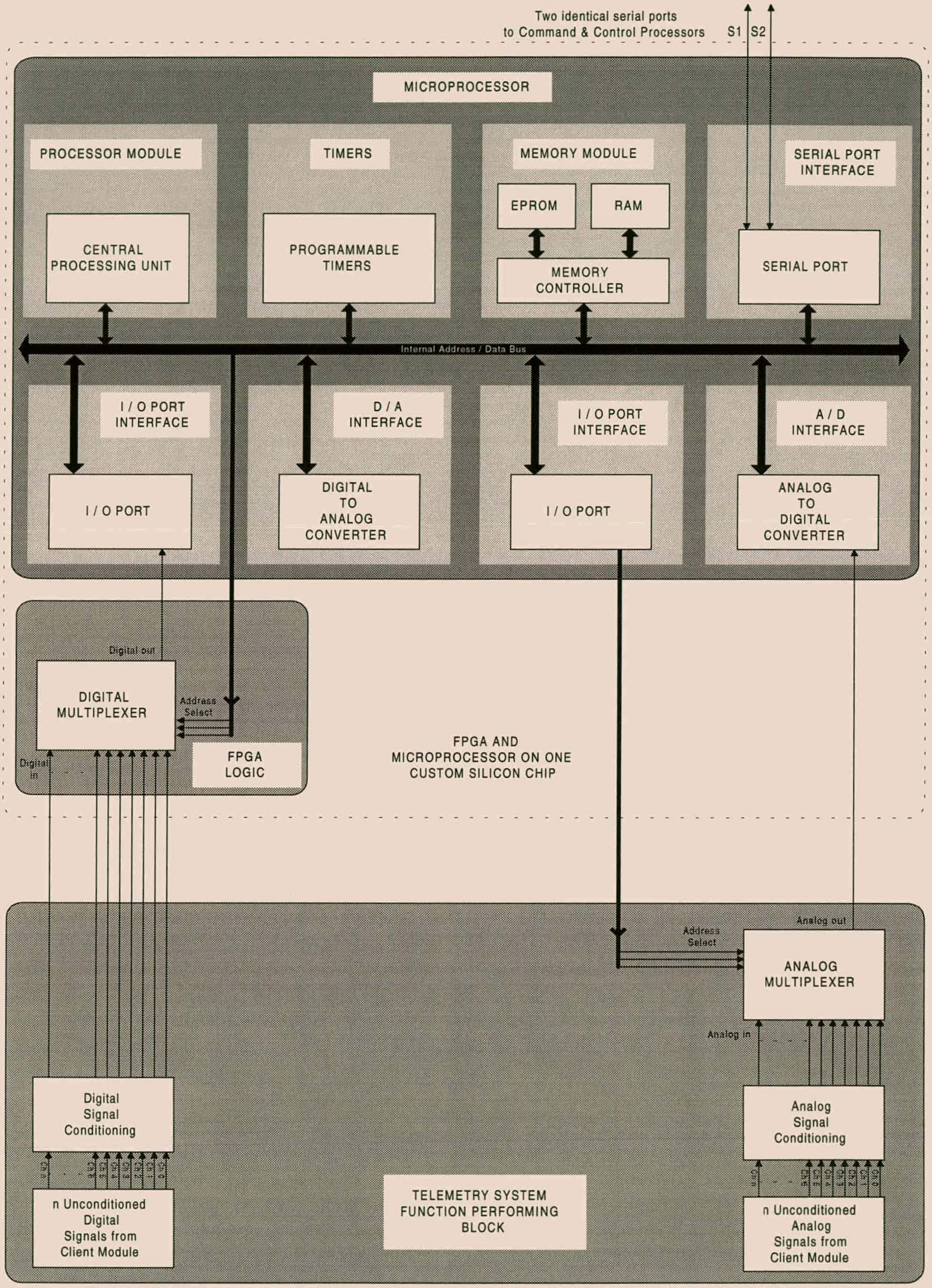

Figure 5.3 - FPGA and Microprocessor on One Custom Silicon Chip and Telemetry System Function Performing Block

5.4.1.1 FPGA Logic Configuration

The built in FPGA will be customised for each client module's digital logic requirements. This will optimise the space, weight and the processing speed of the client module. For the telemetry subsystem, a digital multiplexer will be implemented in the built-in FPGA.

As seen in Figure 5.3, the I / O port from the microprocessor can address select the digital multiplexer that is implemented by the FPGA logic as to which signals to select to input to the I / O port of the of the microprocessor at any given time.

5.4.1.2 Telemetry System Function Performing Block

5.4.1.2.1 Analog Signals from Subsystem

Analog signals from the client module are conditioned by the analog signal conditioning circuit to be within 0 and 5 volts. These conditioned signals are input to an analog multiplexer. The I / O port from the microprocessor can address select the analog multiplexer as to which signals to select to input to the analog to digital converter of the microprocessor at any given time.

5.4.1.2.2 Digital Signals from Client module

Digital signals from the client module are conditioned by the digital signal conditioning circuit to be within 0 and 5 volts. These conditioned signals are input to the digital multiplexer (implemented by the built-in FPGA logic). The

I / O port from the microprocessor can address select the FPGA digital multiplexer as to which signals to select to input to the I / O port of the of the microprocessor at any given time.

5.4.2 Decentralised Telemetry

Figure 5.4 below is replica of Figure 5.2. As discussed in Chapter 5, SUNSAT-2R architecture consists of generic building blocks that have their own intelligence and are connected in a star like network to the satellites two main Command and Control (C&C) processors via two identical serial ports over which commands are received and replies sent.

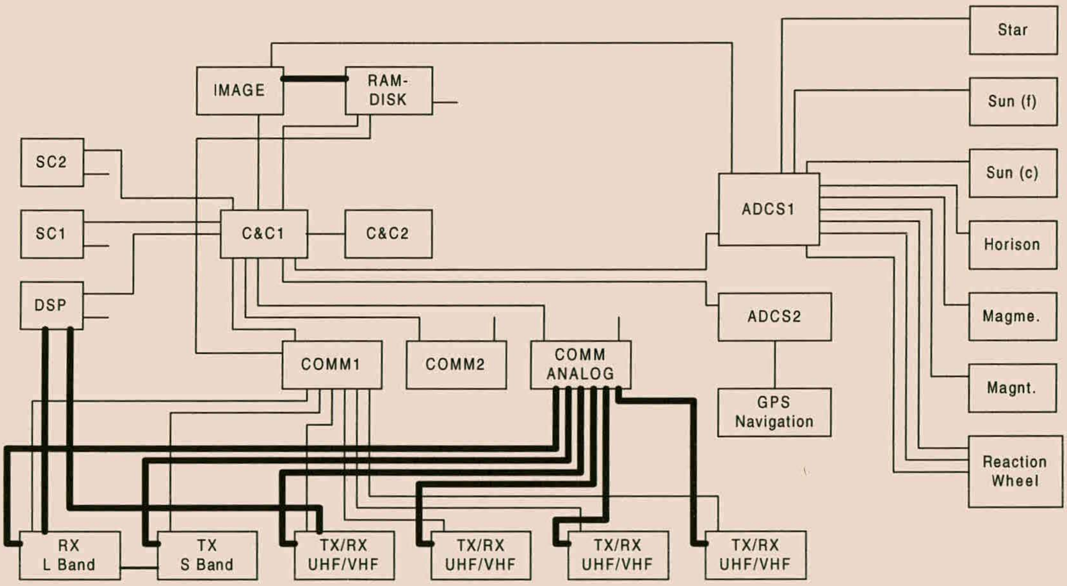

Figure 5.4 - Decentralised Telemetry Structure

As opposed to the SUNSAT-1R architecture where there communication cable harness consisted of over 15 signal lines per client module to the central processors, the new architecture has only 2 (Serial port 1 and Serial port 2). This reduced number of communication cables will optimise space, weight and data integrity.

5.5 CONCERNS AND ADVANTAGES OF THE NEW ARCHITECTURE

A concern in the new proposed architecture is the reliance on microprocessors. SUNSAT-2R does not support any hardware based telemetry function as in SUNSAT-1R. The telemetry function is totally reliant on the client module FPGA microprocessor. However, experiences in LEO have indicated that microcontrollers such as the 8031 and H-8 are reliable in use.

However, use of the FPGA microprocessor will optimise the weight, size and processing speed of the generic building blocks. Use of only 2 serial ports for communication between the generic building blocks and the central command and control processors optimises the weight and sizes of the communication cable harness and optimises data integrity.

An additional advantage of this architecture is, that if a component with a specific reliability is required, space qualified components can be used on that specific building block.

6 CONCLUSION

The current SUNSAT telemetry system was evaluated. The system was found to be satisfactory in its current form to provide the groundstation with information about the health of the satellite. Analytical data was not possible to compile since SUNSAT is currently functional in space. Hence, future roles of SUNSAT were proposed and investigated and the effectiveness, performance and integrity in these new roles evaluated based on the findings in technical articles on similar topics. These future roles proposed include SUNSAT as a multi-satellite with multiple groundstation configuration. An integrity checking system was investigated and proposed to ascertain the validity of telemetry received as well as a software package to evaluate the performance of SUNSAT.

A two-layer SUNSAT LEO satellite communications network was proposed and investigated for the future SUNSAT model. The performance of this configuration was evaluated using the findings of a technical article based on a similar investigation. It was concluded that increasing the number of lower layer satellites reduces the blocking rate. It was further discovered that raising the altitude of the upper layer satellite did not severely worsen the performance, but dramatically reduced the number of satellites.

A multi-SUNSAT, multi-groundstation configuration was proposed and investigated and the traffic performance evaluated based on the findings of a technical article. It was concluded that reconfiguration probability of data bursts decreased by reallotment thereby increasing channel efficiency. A real-time database on the groundstation was proposed and investigated to validate the integrity of SUNSAT's telemetry data received. It was concluded that high data integrity levels could be realised with such a proposal. Finally, a software package was proposed and investigated to evaluate the performance of SUNSAT with adaptative allocation of onboard common resources. The package was found to furnish straightforward indications about the performance of the system.

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APPENDIX A

INTEGRATING PROCESSORS AND RECONFIGURABLE LOGIC

Several research efforts have begun to look at the issues associated with coupling processors and reconfigurable logic on a single die. Details are listed at the Internet Site: http://http.cs.berkeley.edu/research/projects/brass/reproc.html

Following, is a short description of the various projects documented:

1. PRISM - PRISM is, perhaps, the earliest work looking directly at Processor and FPGA co-operation on computing tasks. Peter Athanas' thesis deals with compilation for mixed architectures and touches briefly on integration options.

2. DPGA - coupled Microprocessors – André de Hon's FCCM'94 paper [PS] [HTML] is one early description of the concept along with the motivation for coupling the two units - but the paper is weak on details and costs. A later technical report [PS] [HTML] catalogs architectural options for integration. His more recent work (e.g. [TR blurb]) has begun to quantify some of the areas and costs which were missing from the earliest work.

3. PRISC - Razdan and Smith developed a system to automatically extract code for an integrated reconfigurable accelerator from conventional processor executables. [Razdan Thesis Abstract] [Razdan Thesis] [Micro'94] [ICCD'94]

4. Cypris Crypto Processor - Lockheed Martin/NSA developed an encryption processor [may need netscape to view properly] which features an integrated PLA structure for high-speed, programmable, cryptographic applications.

5. OneChip - Ralph Wittig developed a detailed architecture for such an integrated systems and explored a number of application examples. [OneChip documentation]

6. Garp - Garp is a microprocessor core with a programmable gate array coprocessor, integrated on the same chip under development at UC Berkeley. [architecture] [compilation]

7. Chimaera - Chimaera is a reconfigurable functional unit in the spirit of the PRISC reconfigurable PFU, under development at Northwestern. [overview and paper links]

8. NAPA - NAPA couples National Semiconductor's CLAY array with a RISC processor core for use in embedded signal processing applications. [National Semiconductor ACS Web Page]

9. Modelling - Albaharna Osama has a series of papers [ISCAS'94] [ICCD'94] [FCCM'96] modelling the area-time costs/benefits for processors and reconfigurable architectures. [email <a.osama@ic.ac.uk>]

10. RISC + FPGA case study - Pramod Viswanath and Sriram Rajamani did a quantitative case study on the effects of several processor-reconfigurable array interface issues. [Project Report Page]