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Design Elements of Satellite Telemetry, Tracking and Control Subsystems for the Proposed Nigerian Made Satellite

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ABSTRACT: *The indispensability of Telemetry, Tracking and Control (TT&C) as the brain and operating system of all Satellite or Spacecraft missions is well known. The Centre for Satellite Technology Development (CSTD) in Nigeria has recently initiated a SPIRE (Satellites to Promote Instructional and Research Experiments) program desired to develop and test an engineering model of a micro-satellite as a precursor to the proposed indigenous development and launch of made in Nigeria Satellite.This paper reviews the essential elements necessary for the design and implementation of TT&C, the important component of the proposed Satellite subsystem. The basic components, design overview, programming procedure of TT&C subsystems are presented, while the functions and relationships between various subsystems are highlighted.*

KEYWORD: *TT&C, Ranging, Transducer, Satellite Telemetry, Subsystem*

I. INTRODUCTION

The Centre for Satellite Technology Development (CSTD), is an Activity Centre of the National Space Research and Development Agency (NASRDA). Among its activities is to research, develop, build and launch a Nigerian made Satellite before the year 2020 in response to the mandate/challenge of the Federal Government. In this regard CSTD initiated a program called SPIRE (Satellites to Promote Instructional and Research Experiments), in collaboration with Nigerian Universities, the private sector and Nigerian Diaspora.

Among the Objectives of SPIRE is to design, fabricate, integrate and test an engineering model of a flexible, multi-mission micro-satellite which, among other things shall meet the nation's healthcare and communications needs [1]. This engineering model will serve as a precursor to the proposed Nigerian made Satellite as ordered by the Government of Nigeria. To achieve objectives of the SPIRE programme, CSTD has set up different working groups/teams among which is: The Tracking, Telemetry and Control Team (TT&C) for which this author is a Team Leader. Our first mandate, among others, is to Design and Implement a communication subsystem that will ensure effective and secure communications link between the satellite in orbit and the ground station.

This paper presents the design overview of Telemetry, Tracking and Control subsystem for the proposed Nigerian made Satellite. The Subject matter, TT&C network and functions, programming procedure, and general subsystem functions are presented.

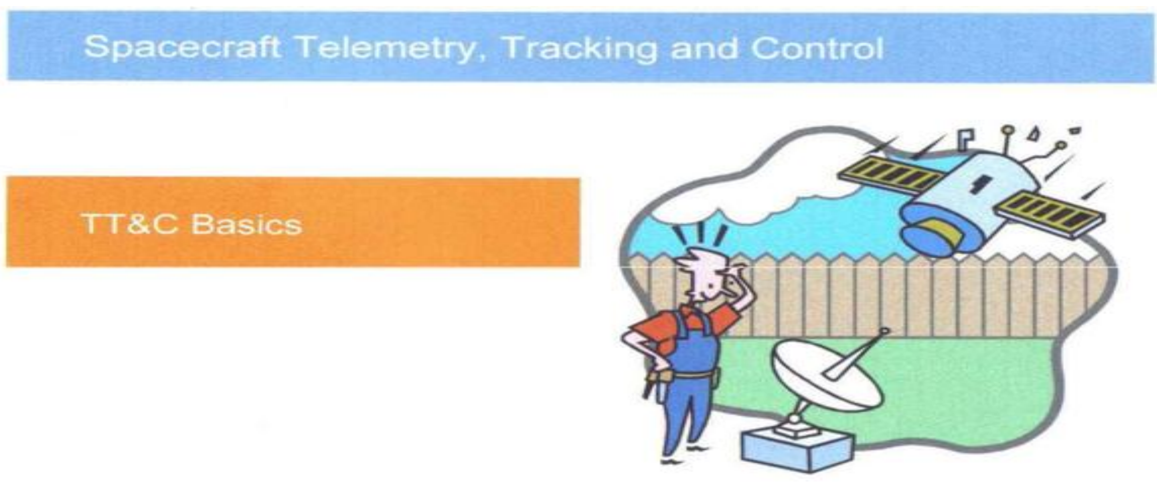


Fig.1. TT&C Basics

Fig.2. TT&C Illustration for French SPOT4 Satellite with Ground Station in CNES
This is a "duplex" link (two-way communication system). Source: CNES [3].

II. OVERVIEW

- The telemetry, tracking and control subsystem provides vital communication toand from the spacecraft.
- TT&C is the only way to observe and to control the spacecraft s functions andcondition from the ground.
- In TT&C (Telemetry, Tracking and Control), the Spacecraft status informationis received at the control Station (Telemetry), the command and control signalis thereafter sent to the Spacecraft (Tele-command/Control), and distance to theSpacecraft and Spacecraft velocity are then measured (Ranging/Tracking); [2], [4].

2.1 Telemetry

In one direction (satellite to ground), Fig.2, the link is used to monitor the satellite through status reports and anomalies detected by the onboard computer; this is telemetry. Telemetry is a set of measurements taken on board the satellite and then sent to the operations control centre. The measurements describe the satellite, subsystem by subsystem. Measurements concern magnitudes as varied as temperatures, voltages, currents etc. For example, if we consider the solar array subsystem, we need to know the output voltage and current at all times.

2.2 Command

In the other direction (ground to satellite), Fig.2, the link is used either for routine programming (commercial imaging requested by Spot Image) or for sending commands to carry out specific actions to handle events as required (orbital maneuvers, equipment tests, anomalies, failures etc.); this is the command link.

Although modern satellites operate automatically, they still need to receive commands from the ground. This need is particularly obvious during the satellite attitude acquisition phase. During this critical phase, the satellite needs to be very closely controlled from the operations control centre. Once the solar arrays have been automatically deployed, commands sent by the control centre switch on the equipment that was off during the launch: recorders, payloads and passengers if any.

2.3 Tracking

The same link is used for tracking. This term describes measurements taken to accurately locate the orbiting satellite (**orbit determination**);[5]. This involves:

- Measuring the time taken by RF signals for the round trip journey (station - satellite- station). By measuring the time taken, it is possible to calculate the distance between the station and the satellite, an operation known as Ranging.
- Measuring, based on the Doppler effect, the frequency shift due to satellite velocity; this measurement is used to calculate satellite range rate.
- Measuring antenna orientation with respect to the north (azimuth) and the horizon (elevation), when the antenna is pointing towards the satellite. The complementary elevation and azimuth measurements are indispensable for determining the exact orbital position and thus for accurately calculating the satellite's orbit.

Once these measurements have been taken by the TT&C network, they are sent on to the network's customer (in this case the operations control centre).

III. OUTLINE OF TT&C

- TT&C functions and trades
- Command System functions: Encoding/Decoding; Messages; Interfaces
- Telemetry systems: Sensors and transducers; ADC; Formats; Concerns/Design principles

3.1 TT&C Functions

- Carrier tracking
- Command reception and detection
- Telemetry modulation and transmission
- Ranging
- Subsystem operations

3.2 Carrier Tracking

- Two-way coherent communication: Transmitter phase-locks to the received frequency; Transmitted frequency is a specific ratio of the uplink frequency.
- Easy to find and measure the frequency received on the ground
- Doppler shift provides range rate

3.3 Ranging

- Uplink pseudo-random code is detected and retransmitted on the downlink
- Turnaround time provides range
- Ground antenna azimuth and elevation determines satellite angular location

3.4 Subsystem Operations

- Receive commands from Command and Data Handling subsystem
- Provide health and status data to CD&H
- Perform antenna pointing
- Perform mission sequence operations per stored software sequence
- Autonomously select omni-antenna when spacecraft attitude is lost
- Autonomously detect faults and recover communications using stored softwaresequence.

3.5 TT&C Trade Offs

- Antenna size vs transmitter power
- Solid state amplifiers vs travelling wave tube amplifiers
- Spacecraft complexity vs ground complexity

TT&C Interfaces

Subsystem	**Requirement**
Attitude Determination and Control	Antenna Pointing
Command and Data Handlin	Command and Telemetry Data Rates Clock, bit sync and timing requirements Two-way communications requirements Autonomous fault detection and recovery Command and telemetry electrical interface
Electrical Power Subsystem	Distribution Requirements
Thermal/ Structural	Heat sinks for TWTAs Heat dissipation for all active boxes Location of TT&C Subsystem electronics Clear field of view for all antennas
Payload	Storing Mission Data RF and EMC storage requirements Special requirements for modulation and coding

IV. COMMAND SYSTEM

- Reconfigures satellite or subsystems in response to radio signals from the ground; [6].
- Command timing: Immediate; Delayed; Priority driven (ASAP).

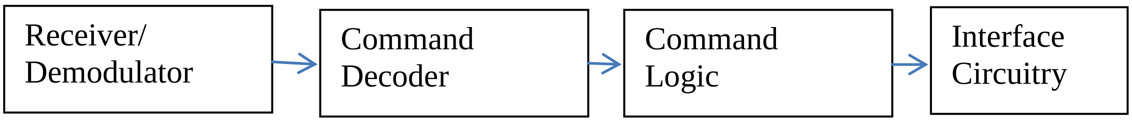
4.1 Command Functions

- Power on/off subsystems
- Change subsystem operating modes
- Control spacecraft guidance and attitude control
- Deploy booms, antennas, solar cell arrays, protective covers
- Upload computer programs

4.2 Command System RF Performance

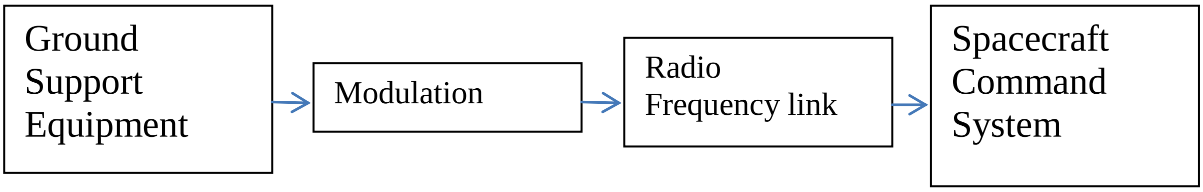
- Frequencies: S-band (1.6 2.2 GHz); C-band (5.9 6.5 GHz); Ku-band (14.0 14.5 GHz).
- BER = 10-6

4.3 Spacecraft Command System Block Diagram



- Decoders reproduce command messages and produce lock/enable and clock signals
- Command logic validates the command: Default is to reject if any uncertainty of validity; Drives appropriate interface circuitry

4.3 Complete Command System



- GSE operator selects command mnemonic
- Software creates command message in appropriate format and encodes it
- Batch commands/macros
- Pulse code modulation (PCM)
- Phase shift keying (PSK)
- Frequency shift keying (FSK)

4.5 Command Decoders

- Detects PCM encoding and outputs binary stream in non-return-to-zero format
- Outputs clock signal
- Outputs lock/enable signal
- Activates downstream command subsystem components
- Decentralized decoding reduces harness mass

4.6 Secure Command Links

- Encryption
- Authentication

4.7 Command Message Components

- Input checkerboard bits
- Synchronization (Barker word) bits
- Command bits
- Error detection bits

4.8 Command Messages

- Spacecraft address
- Command type: Relay commands; Pulse commands; Level commands; Data commands
- Command select

- Error detection and correction
- Multiple commands

4.9 Command Logic

- Decodes command
- Validates command: Correct address; EDAC; Valid command; Valid timing; Authenticated
- Activates circuitry

4.10 Interface Circuitry

- Latching relays with telltales
- Pulse commands
- Level commands
- Data commands: Serial (enable, data and clock); Parallel.

V. TELEMETRY SYSTEMS

- Measure physical properties from afar: Status of spacecraft resources, health, attitude, and operation; Scientific data; Spacecraft orbit and timing data for ground navigation; Images; Tracked object location; Relayed data.

5.1 Telemetry System RF Performance

- Frequencies: S-band (2.2 2.3 GHz); C-band (3.7 4.2 GHz); Ku-band (11.7 12.2 GHz).
- BER = 10^{-5}

5.2 Sensors and Transducers

- Sensors change state as a function of an external event
- Transducers convert energy from one form to another
- Outputs can be: Resistance; Capacitance; Current; Voltage.

5.3 Signal Conditioning and Selection

- Conditioning ensures proper level: dynamic range; frequency response; impedance; ground reference; common mode rejection.
- Commutation selects the proper sensor at a given time
- Sampling frequency determined by the Nyquist criteria

5.4 Analog to Digital Conversion

- Converts voltages (0 5.1 v, or -2.56 to 2.54 v) to 2n-1 discrete values
- Quantization error decreases as n increases

Type Conversion	Rate	Word Size	Power
High Speed ADC	50*106 /sec	8 bit	2.5W
High Resolution ADC	1*105 /sec	16 bit	1.5 W
Low Power ADC	2.5*104 /sec	8 bit	0.005 W

5.5 Telemetry Processing

- Compression
- Analysis for autonomous systems
- Formatting
- Storage

5.6 Telemetry Formats

- Synchronization
- Frame count
- Spacecraft identification

- EDAC
- Frame format identification
- Spacecraft time

5.7 Multiplexing

- Frequency division multiple access
- Time division multiple access
- Code division multiple access

5.8 Commutation in Data Formats

Data type no. 1 bits	Type no. 2 bits	Type no. 3 bits	Type no. 4 bits	Type no. 5 bits	Type no. 6 bits	Type no. 7 bits

- Commutation sequential data time sampling: Data includes major and minor frame identification and EDAC.
- Sub-commutated data given element represents different data in differentframes.
- Super-commutated data given element is found more than once per frame

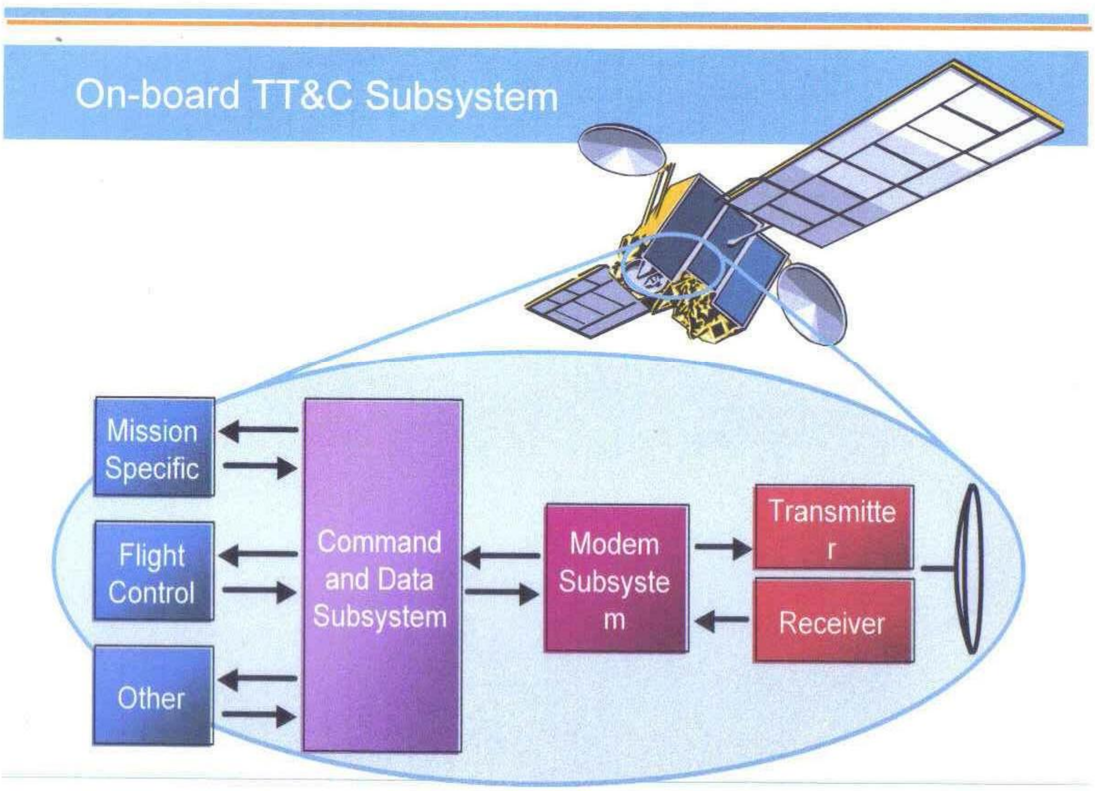


Fig. 3. On-board TT&C Subsystem

5.9 TT&C Network and Satellite Ear

In the example shown in Fig 4, the Satellite equipment is almost exactly the same as that used for ground stations:

- a small network of two linked antennas facing in opposite directions.
  One is on the underside, the other on the topside of the satellite. They cannot be pointed elsewhere, but they cover all the area around the satellite (and so never lose the link, whatever the satellite's attitude in

space). This feature, related to the equipment's size, makes for low gain. It is up to the ground station to raise the gain by tracking the satellite without losing it.

- two transponders in this case.

They have the same modulation / demodulation functions for the 2 GHz frequency as the ground segment. The transponders are very small. Each one transmits 250 mW telemetry and receives command signals of infinitesimal power (measured in pico Watt: 10^{-12} Watt !). The transponders can pick up exceptionally weak signals. The two transponders are coupled (they both receive the same signal and either one can transmit, according to the configuration). Such "redundancy" ensures the system has optimal reliability should one of the modules fail. They are connected to both antennas at the same time via a hybrid coupler which distributes signals in both directions.

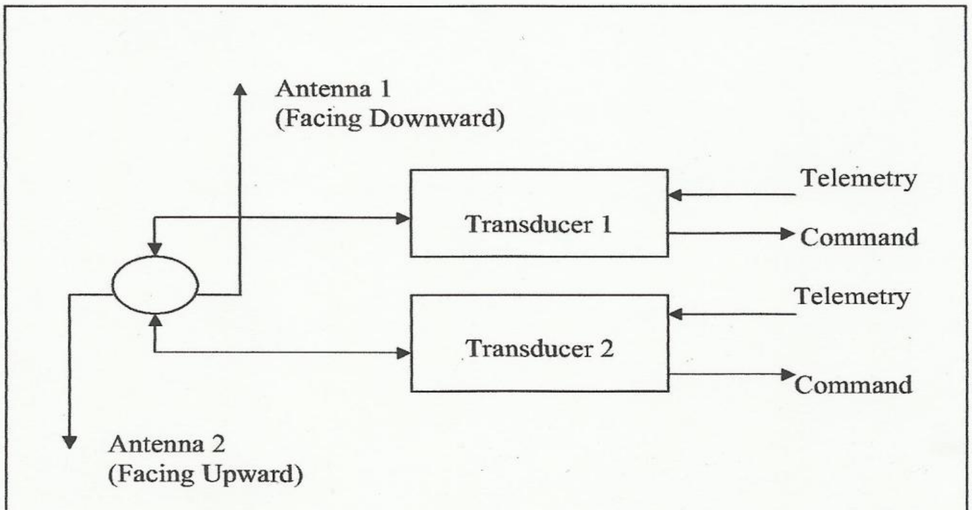


Fig. 4. On board Satellite Ear

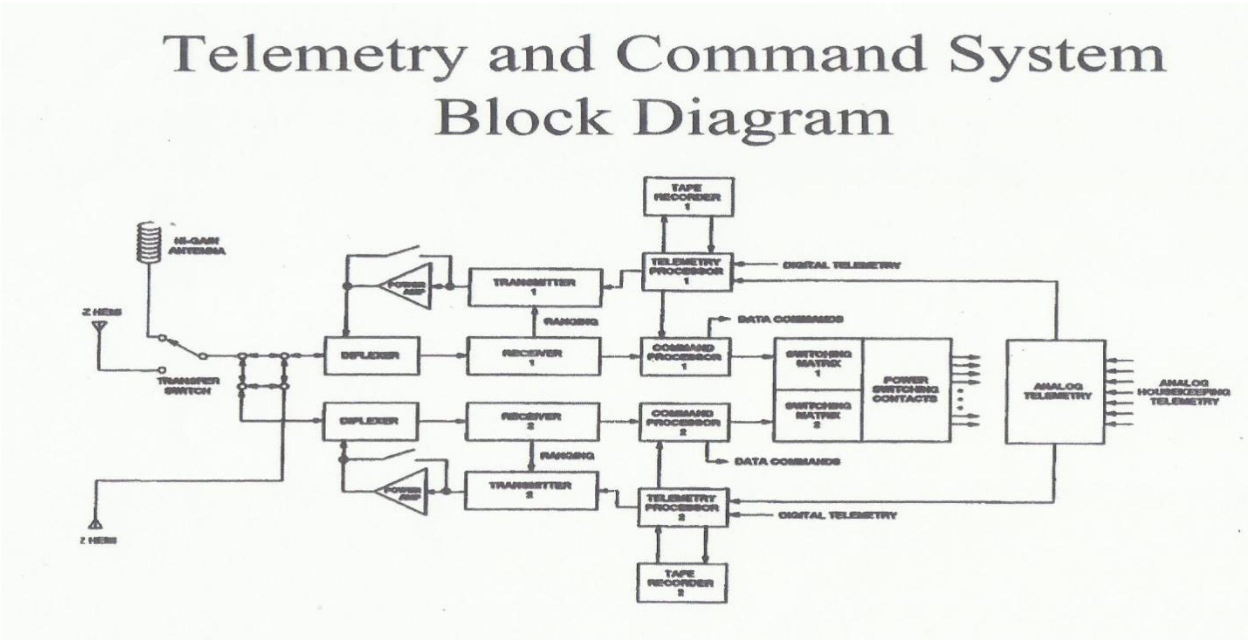


Fig. 5. Telemetry and Command System Block Diagram

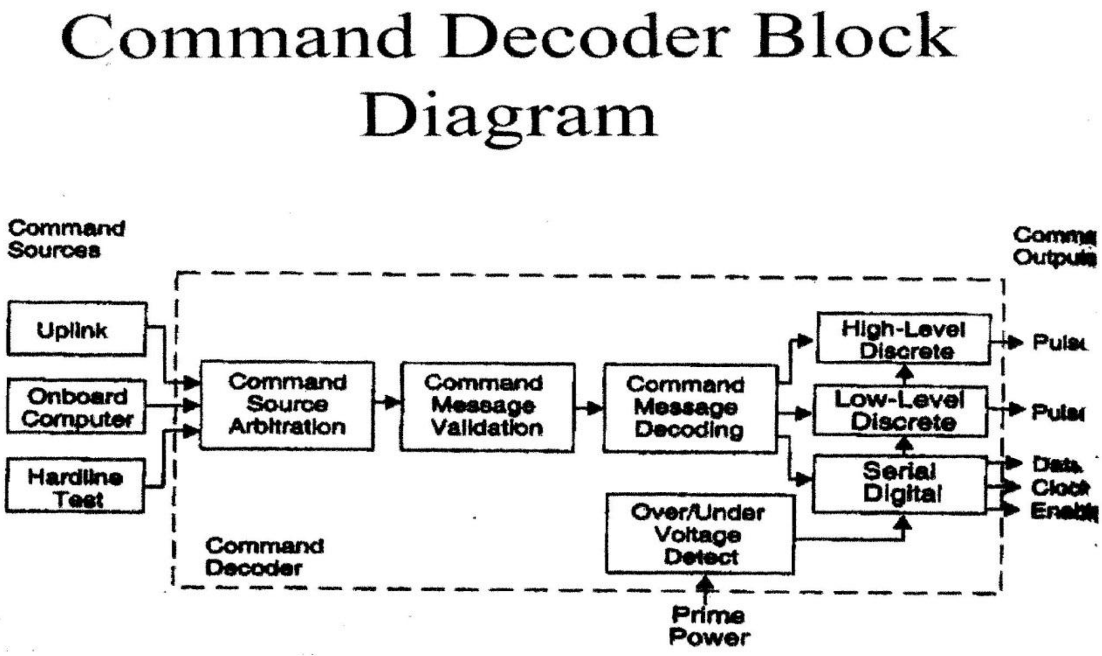


Fig.6. Command Decoder Block Diagram

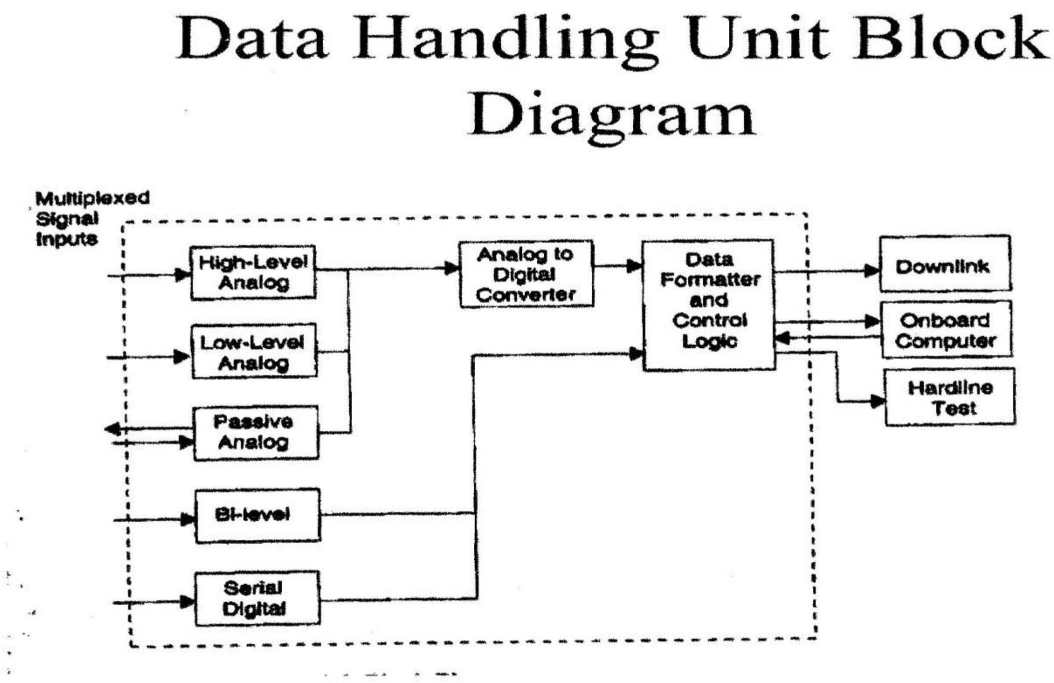


Fig.7. Data Handling Unit Block Diagram

5.10 Command and Data Handling Concerns

- Interfaces to other subsystems must protect the command decoder
- No commands or transient signals may appear on command outputs during application or removal of prime power or during under/over voltage conditions
- If a commands integrity is in doubt, reject it

- Multiple commands are required for critical/ dangerous operations
- No single component failure can result in unintended operation
- No commands shall interrupt the uplink source to the command decoder

5.11 The Programming procedure: Master-Slave Relation

- Each day, On board system groups together customer requests for regions of interest to be acquired the following day. It then sends the relevant work plan to the operations control centre.
- The operations control centre checks the contents of the plan so as to avoid any damage to the satellite. It then converts the plan into commands ready to be sent to the satellite.
- Telemetry and commands are exchanged with the satellite when it comes within range of one of the TT&C network stations.
- Once "radio" contact has been made, the operations control centre receives the housekeeping telemetry, translating it into parameters for display on the control monitors.
- The operators are then able to interpret the parameters. Many of the parameters are also analyzed in real time by software in the operations control centre to assess the satellite's health or draw up commands to be uplinked to the satellite during later passes.
- Rapidly, once the link has been established, and assuming that no anomalies are detected, the operations control centre sends the commands to the satellite as planned.
- Apart from very rare, serious incidents, commands are prepared during the ten minute period before the pass and uploaded to the satellite before it goes out of range again (less than 15 minutes for LEO).
- During this dialogue, the operations control centre is the "master". The relatively intelligent "slave" is the flight software on board the satellite.
- Communication between master and slave takes place using very high frequency radio waves (around 2 GHz) between the transmitting/receiving equipment on the satellite and each ground station in the TT&C network.

VI. CONCLUSIONS

The flight software for SPOT4 runs on a 12 MHz Fairchild 9450 processor (compared with the 100 to 200 MHz processor in your PC) and has a memory of less than 200 kbytes (far less than the 16 or 32 Mbytes of RAM in your computer). It is with such scanty resources that the flight software executes commands one after the other and handles satellite operating modes. The satellite's daily tasks depend on the list of commands sent by the operations control centre. The flight software orders imagery acquisition according to customer requests when the satellite flies over the region of interest. The flight software also carries out the orbit corrections needed to keep the satellite on the correct trajectory. It monitors all the satellite equipment by communicating with each subsystem. The monitoring takes place at 1 Hertz (once every second), 8 Hertz or 32 Hertz. It is designed so that the flight software can take any appropriate action necessary to guarantee that the satellite is not damaged. Should a fault be detected, the flight software continues to fulfill the vital satellite functions, calling upon backup equipment as required. The flight software is not required to locate the faulty part or to continue automatic imagery acquisition without the operations control centre's involvement. The software indicates the anomalies in the telemetry sent to the operations control centre and provides the experts in the Centre with all the information needed to locate the fault. Thus the complete TT&C subsystems required for successful implementation of Nigerian made satellite is realized.

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