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Satellite Telemetry, Tracking and Control System for Nigerian Made Satellite

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***Abstract* - Satellite Telemetry, Tracking and Control (STT&C) is the brain and operating system of all Satellite or Spacecraft missions. The Centre for Satellite Technology Development (CSTD) in Nigeria has initiated a program known as SPIRE (Satellites to Promote Instructional and Research Experiments) for the purpose of developing an engineering model of a micro-satellite as a prototype to an indigenous development and launch of made in Nigeria Satellite.This study reviews the progress made and necessary components for the design and implementation of STT&C including the important components of the Satellite. Also presented are the design overview and the programming procedure ofTT&C subsystems, while the functions and relationships between various subsystems are discussed.**

Keyword: Ranging, Transducer, Satellite Telemetry, Control Subsystem

1.0 INTRODUCTION

The Nigerian Federal Government issued marching orders to Nigerian Scientists and Engineers in our Universities for the development and launch of a Nigerian made Satellite into orbit by the year 2020. The Centre for Satellite Technology Development (CSTD), is an activity Centre of the National Space Research and Development Agency (NASRDA). One of its activities is to research, develop, build and lunch a Nigerian made Satellite 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 and the private sector.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], [2]. This engineering model will serve as a prototype to wholly Nigerian made Satellite to be launched by Nigerians as ordered by the Government of Nigeria. To achieve objectives of the SPIRE program, 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.

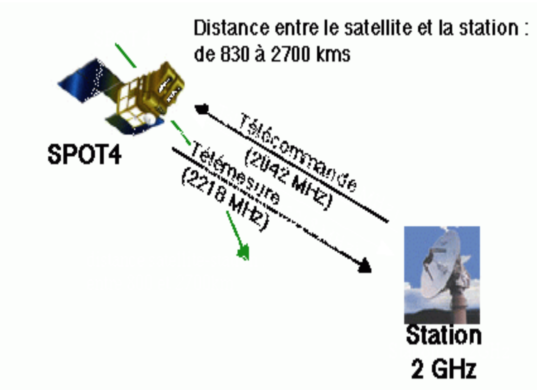

Fig.1. TT&C Illustration for French SPOT4 Satellite with Ground Station in CNES

This is a "duplex" link (two-way communication system). Source: CNES [5].

This paper reviews the progress made so far and presents the design overview of Telemetry, Tracking and Control subsystem for the Nigerian made Satellite modeled after French SPOT4. The TT&C network and functions, programming procedure, and general subsystem relationships are presented. Fig.1 illustrates the TT&C for French Spot 4 Satellite with ground-station in CNES.[3].

2.0 OVERVIEW

The telemetry, tracking and control subsystem provides vital communication link 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].

In one direction (satellite to ground), Fig.1, 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.

In the other direction (ground to satellite), Fig.1, the link is used either for routine programming (commercial imaging requested by Satellite 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.

The same link is used for tracking. This term describes measurements taken to accurately locate the orbiting satellite (**orbit determination**);[6]. 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.

These measurements are taken by the TT&C network and are sent on to the network's customer (the operations control centre) for command and tracking purposes.

3.0. Outline of Telemetry, Tracking and Control Subsystem

The outline includes: TT&C functions and trades offs;Command System functions which involvesEncoding/Decoding,Messages,Interfaces; and the Telemetry systemsthat includesSensors and transducers, Analog to Digital Converters (ADC), Formats,Concerns and Design principles.

3.1 *TT&C Functions*

This includes the Carrier tracking for signal tracking, the Command reception and detection, the Telemetry modulation and transmission, Ranging, and Subsystem operations.

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

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

Subsystem Operations: Receive commands from Command and Data Handling subsystem (CD&), 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, andAutonomously detect faults and recover communications using stored softwaresequence.

3.2 TT&C Trade Offs

The following Trade Offs are ensured in the overall design: Antenna size vs. transmitter power; Solid state amplifiers vs. travelling wave tube amplifiers; Spacecraft complexity vs. ground complexity.

3.3. TT&C Interfaces

The TT&C Interfaces are provided according to subsystems and requirements as listed in the table below.

Table 1. 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

3.3 *Command System Functions*

The Command System reconfigures the satellite or subsystems in response to radio signals from the ground [7], [8].

Command timing is configured forImmediate,Delayed, andPriority driven (ASAP).

Command Functions include: Power on/off subsystems, Change subsystem operating modes, Control spacecraft guidance and attitude control, **(**Deploy booms, antennas, solar cell arrays, protective covers), and Upload computer programs.

Command System RF Performanceinvolves 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}.

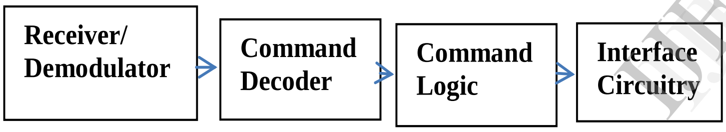

Fig. 2A. Spacecraft Command System Block Diagram

Fig.2A. illustrates the Satellites Command System Block diagram and showing the command chain. The Decoders reproduce command messages from the receiver/demodulator and produce lock/enable and clock signals. The Command logic validates the command: Default is to reject if there is any uncertainty of validity anddrives appropriate interface circuitry.

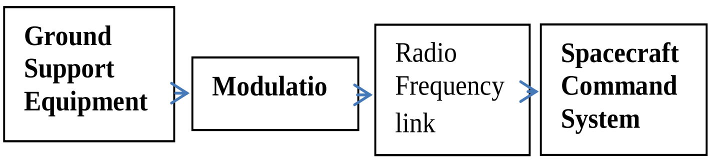

Fig.2B. Block Diagram of a Complete Command System

The complete command system is illustrated in the Block diagram of Fig. 2B. The ground support operator (GSE) selects appropriate command mnemonic, while Software creates command message in appropriate format and encodes it: Batch commands/macros, Pulse code modulation (PCM), Phase shift keying (PSK), and Frequency shift keying (FSK).

Command Decoders: Detect 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.

Secure Command Linksis provided via Encryption and Authentication.

Command Message ComponentsinvolveInput checkerboard bits, Synchronization (Barker word) bits, Command bits, and Error detection bits.

Command Messages include: Spacecraft address, Command type: (Relay commands; Pulse commands; Level commands; Data commands), Command select, Error detection and correction, and Multiple commands.

Command Logic Decodes command, Validates command: (Correct address; EDAC; Valid command; Valid timing; Authenticated), and Activates circuitry.

Interface Circuitryinvolves latching relays with telltales, Pulse commands, Level commands, Data commands: Serial (enable, data and clock) andParallel.

3.4 *Telemetry Systems*

The Telemetry systems measure physical properties from afar for instance the Status of satellite resources such as health, attitude, and operation; measure Scientific data; Satellite orbit and timing data for ground navigation; Images; Tracked object location; Relayed data.

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}**.**

Sensors and Transducers: Sensors change state as a function of an external event**,** while Transducers convert energy from one form to another. TheOutputs can be: Resistance; Capacitance; Current; Voltage.

Signal Conditioning and Selection: SignalConditioning ensures proper signal 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.

Telemetry Processing: involves Signal Compression, Analysis for autonomous systems, Formatting and Storage.

Telemetry Formats: Synchronization, Frame count, Satellite identification, EDAC, Frame format identification, and Spacecraft time.

3.4.1 *Analog to Digital Conversion*

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

Table 3. Analog to Digital Conversion Mechanism

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	0.05

Multiplexing involves: Frequency division multiple access, Time division multiple access, Code division multiple access.

Table 4. 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.

4.0. Design Configurations: On-board TT&C Subsystem

The On-board Telemetry, Tracking and Control Subsystem is illustrated in Fig. 3. The On-board TT&C showsvarious communications pathways between Mission specific, Flight Control, other objectives, and Transmit/Receive antenna via Command and Data Subsystem.

The Modem Subsystem serves to rout the signal to the appropriate Subsystems of the TT&C as shown on the block diagram of Fig.3.

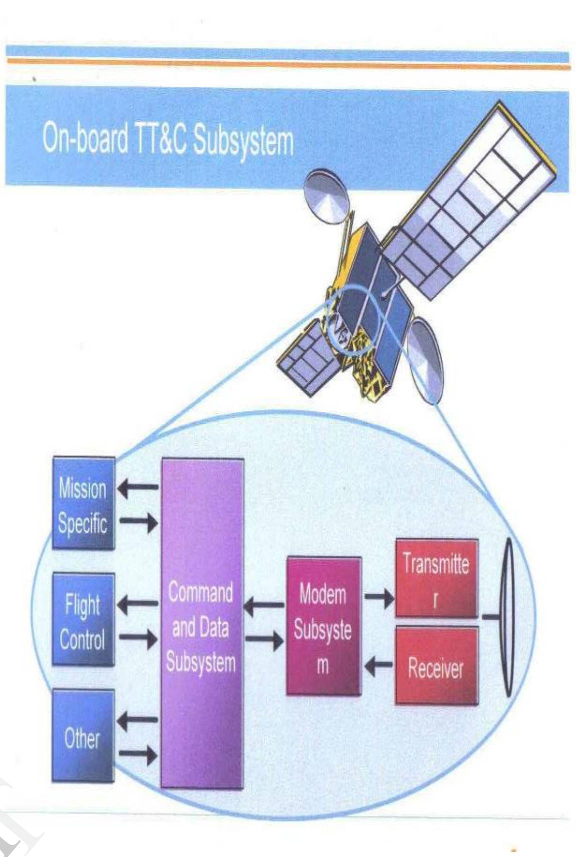

Fig. 3. On-board TT&C Subsystem

4.1 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:

It includes 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 as per the trade offs. It is up to the ground station to raise the gain by tracking the satellite without losing it. It incorporates two transponders also for this example.

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.

In Fig.5 the Telemetry and Command System block diagram is illustrated while the Command Decoder Block diagram is shown in Fig.6. In Fig.7, theblock diagram of Data Handling unitshows how the multiplexed signal input is handled via the Analog to Digital Converter between the Downlink and Onboard Subsystems.

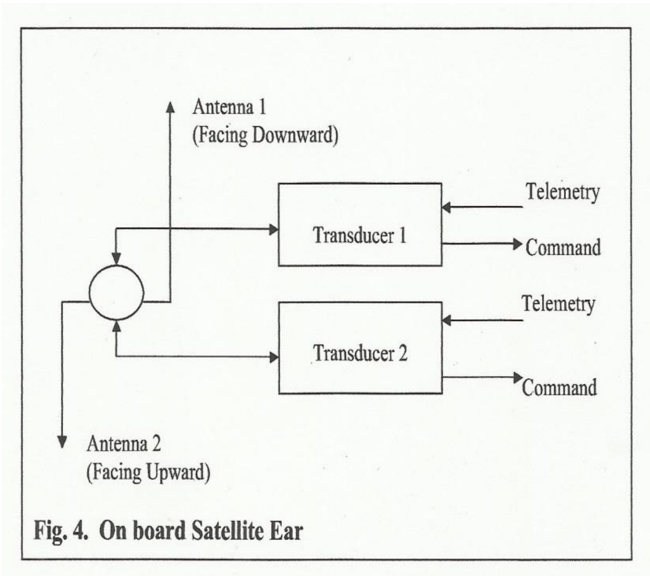

Fig. 4. On board Satellite Ear

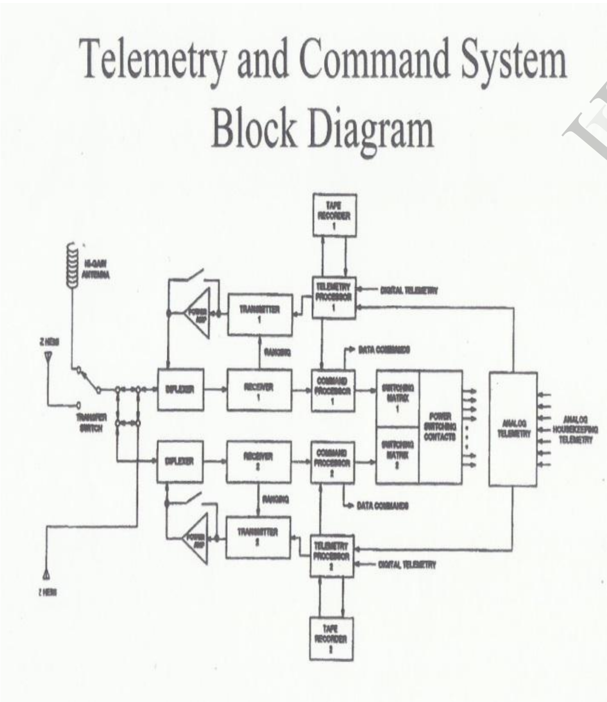

Fig. 5. Telemetry and Command System Block Diagram

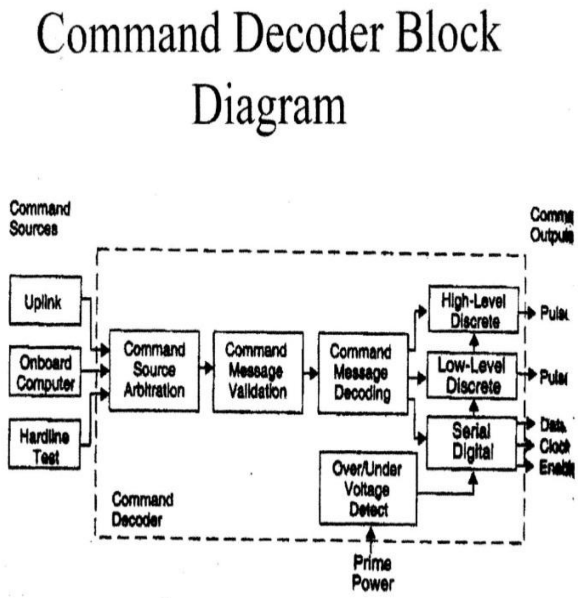

Fig.6. Command Decoder Block Diagram

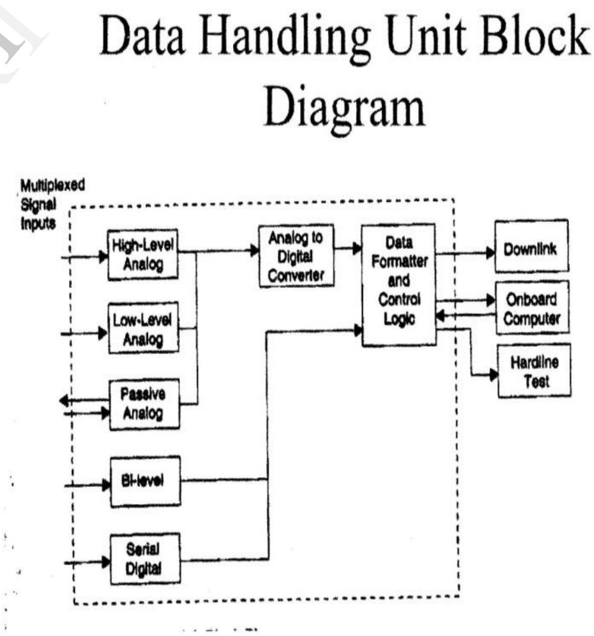

Fig.7. Data Handling Unit Block Diagram

4.2 *Command and Data Handling Concerns*

Interfaces to other subsystems must protect the command decoder. No commands or transient signals may appear on command outputs duringapplication or removal of prime power or during under/over voltage conditions. If a command's integrity is in doubt, It must be rejected. Multiple commands are required for critical/ dangerous operations to ensure accuracy of operation. No single component failure can result in unintended operation and No commands shall interrupt the uplink source to the command decoder.

4.3 *The Programming procedure: Master-Slave Relation*

The following procedure shall be followed. Each day, On board system groups together all customer requests for regions ofinterest to be acquired the following day. It then sends the relevant work planto the operations control centre.The operations control centre shall then check the contents of the plan so as to avoid anydamage to the satellite. It then converts the plan into commands ready to besent to the satellite.

Telemetry and commands are exchanged with the satellite when it comeswithin range of one of the TT&C network stations.Once "radio" contact has been made, the operations control centre then receives thehousekeeping telemetry, translating it into parameters for display on thecontrol monitors.The operators are then able to interpret the parameters. Many of the parametersare also analyzed in real time by software in the operations control centre toassess the satellite's health or draw up commands to be uplinked to the satelliteduring later passes.Rapidly, once the link has been established, and assuming that no anomaliesare detected, the operations control centre sends the commands to the satelliteas planned.Apart from very rare, serious incidents, commands are prepared during the tenminute period before the pass and then uploaded to the satellite before it goes out ofrange again (less than 15 minutes for LEO).During this dialogue, the operations control centre is the "master". Therelatively intelligent "slave" is the flight software on board the satellite.Communication between master and slave takes place using very highfrequency radio waves (around 2 GHz) between the transmitting/receivingequipment on the satellite and each ground station in the TT&C network.

5.0 CONCLUSIONS

In this study the designoverview, outline, and the programming procedure of TT&C subsystems for the Nigerian made satellite modeled after SPOT4 has been presented.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 communicatingwith each subsystem. 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.

It is expected that Nigerian Engineers and Scientists shall soon build and launch an indigenous satellite into the orbit for instructional and research experiments. This will complement the Nigcomsat-1 and Nigerian Sat X earlier launched by Nigeria in collaboration with China Great Walls industries.

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