

Microprocessor-based on-board telecommand system for spacecraft

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Abstract

The microprocessor-based on-board telecommand system for ISRO spacecraft in general and Stretched Rohini Satellite Series in particular is described in this paper. The system design and implementation efforts are highlighted.

Key words: Spacecraft or satellite, SROSS, telecommand (TC), command (CMD) microprocessor, reliable system, CMD word, frame and systems, coding, BCH code, on-board CMD generation, time-tag CMD.

1. Introduction

In the spacecraft data communication system, the telecommand (TC) function involves the transmission of command (CMD) information from the ground to the spacecraft. CMD is needed to control the spacecraft functions and direct it to take specified actions, with specified parameters at a definite time. A TC system should reliably work in all circumstances, to achieve successfully the spacecraft mission objectives. The on-board TC system for the Aryabhata¹, first Indian satellite, was simple with limited CMD capabilities, but as the Indian space programme has evolved during the last decade, the on-board TC system² has become complex with sophisticated CMD capabilities for Stretched Rohini Satellite Series (SROSS) spacecraft.

2. Design objectives

The SROSS on-board TC system design objectives are:

- (i) The uplink CMD performance should be error free. To meet this requirement, a coding scheme is employed.
- (ii) The system should be highly reliable and single-point failure should not be catastrophic.
- (iii) The weight and power consumption requirement of the system should be kept as minimum as possible.

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- (iv) The on-board TC system should be flexible and be able to meet and control the CMD management requirement of the SROSS, *i.e.*, the time-tag command (TT CMD) operation, CMD sequence execution, and auto on-board command generation (OBCCG).
- (v) The system should be standardized, for quick repetitive use by different SROSS missions.

3. System implementation details

SROSS is a complex satellite³, having highly demanding CMD capabilities along with severe constraints on weight, volume and power consumption for the system design. The system is designed and implemented taking the following into consideration:

- (i) use of the in-orbit CMD system performance experiences of Aryabhata, Bhaskara, APPLE and Rohini satellites.
- (ii) use of highly reliable, space-qualified, and flight-proven, low-power consumption devices and components.
- (iii) use of flight-proven redundant hardware decoder unit for real-time uplink commanding.
- (iv) use of microprocessor-based sub-system to meet the sophisticated CMD capabilities.
- (v) use of a highly optimized design of the printed circuit board, and double-side component-mounting technique is employed to keep the weight of the system to a minimum.

3.1 Command format and structure

The hierarchy of the CMD, in order, is bit, byte, word, frame and message.

3.1.1 The command word

The length of the CMD word is 32 bits. It comprises three parts, *i.e.*, address and mode bytes, and two bytes of information. Address is assigned to select a particular decoder unit in a specific satellite for CMD execution. Multiple satellites (max. no. 32), each with multiple decoder (max. no. 4), can be commanded. The mode is assigned for a variety of CMD information transfer to the spacecraft. For SROSS, three modes of CMD information are used: 1. real-time CMD execution mode, 2. time-tag CMD store mode, and 3. TC-function CMD mode.

The 16-bit length CMD information on board the spacecraft is used in various ways, depending on the mode assignment.

3.1.2 The command frame

The 32-bit CMD word is encoded into 56-bit long code word by adding 24 parity check bits by the use of a coding technique. The 56-bit code sequence is called a 'command frame'.

3.1.3 The command message

A single CMD transmission to the spacecraft consists of four of the above defined CMD frames with a blank space of 10 bits in between frames. This is called the 'command message'.

At ground, this PCM CMD message modulates two sub-carriers. The base band PCM/FSK CMD signal frequency modulates a 70-KHz sub-carrier, which in turn phase modulates the main carrier in S-band transmission scheme. With VHF scheme, PCM/FSK CMD signal amplitude modulates the main carrier.

3.2 Uplink telecommand specifications

The command word format and the command structure are given in fig. 1.

3.3 Command code selection

The spacecraft telecommanding requires a) very high probability for correct CMD execution, b) low probability for CMD rejection, and c) very very low probability for spurious CMD execution.

To achieve these objectives, the CMD word is encoded before transmitting to the spacecraft. The coding is used to combat the transmission error introduced by the channel. The on-board decoder function is to decode the CMD correctly at its output by employing a suitable decoding strategy.

Basically, the CMD is in bursts, and requires a small number of binary bits to be transmitted. Block coding is most suitable for the spacecraft commanding. The BCH binary linear cyclic block code is selected for its good hamming distance, for a given information and block length. The BCH code⁴ selected is 63, 39, 9 and is suitably shortened to 56, 32, 9 to accommodate the 32-bit CMD word. The shortening of the code also helps to combat the problem associated with the cyclic shift property of the linear block code.

The generator matrix polynomial equation derived is

$$G(X) = X^{24} + X^{23} + X^{22} + X^{20} + X^{19} + X^{17} + X^{16} + X^{13} + X^{10} + X^9 \\ + X^8 + X^6 + X^5 + X^4 + X^2 + X + 1.$$

The encoding at ground encoder and decoding on board the spacecraft by decoder is implemented using parity check polynomial equation in the form

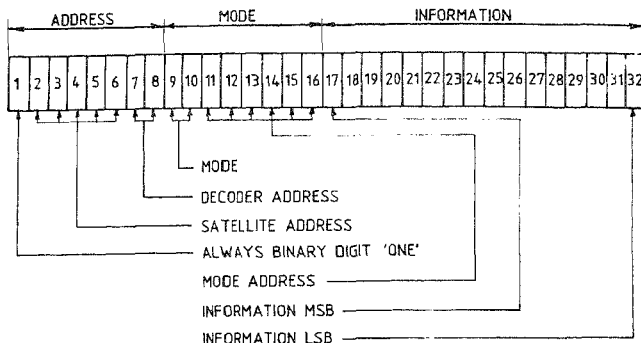
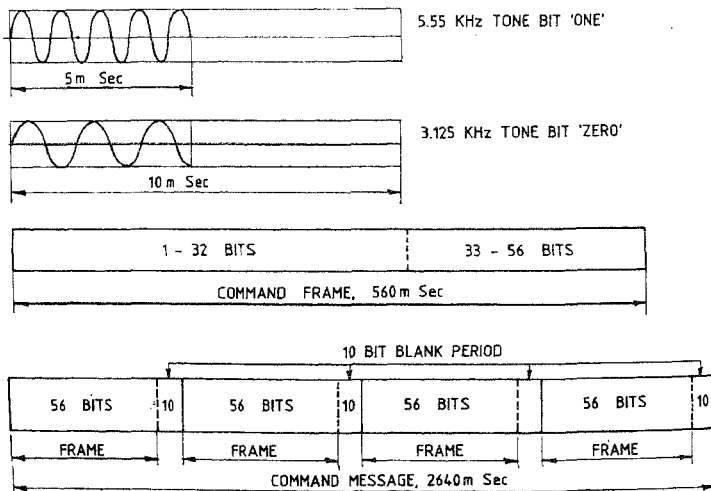
(a) **Command word format**(b) **Command structure**

FIG. 1. The command word and command structure.

$$\begin{aligned}
 H(X) = & X^{39} + X^{38} + X^{36} + X^{34} + X^{32} + X^{30} + X^{29} + X^{28} + X^{27} + X^{24} + X^{23} \\
 & + X^{22} + X^{21} + X^{19} + X^{18} + X^{17} + X^{16} + X^{15} + X^{14} + X^{11} \\
 & + X^9 + X^8 + X^6 + X^5 + X^3 + X + 1.
 \end{aligned}$$

It is necessary to measure or estimate the CMD decoder output error rate. The result of measurement or estimation will depend not only on the parameters of the code but also on the error statistics of the channel (channel model) and on the decoding method. The actual decoder implementation or algorithm is important, because this determines the multiplication or propagation effects, which in turn determine the exact CMD output error rate. Thus, the calculation of CMD output error rate is in general a complex procedure and often, simulation is used to determine the CMD error rate performance.

For the decoder implementation, two strategies can be employed:

- (i) Error detection in CMD, which requires more than one frame of CMD to be transmitted as CMD message.
- (ii) Error detection and correction, which although requires only one CMD frame, calls for complicated on-board correction procedure.

The first strategy is chosen for on-board decoding, with four CMD frames making one CMD message. This scheme is simple and easy to implement. Assuming a binary symmetric channel (BSC) with channel-error probability rate $Pe = 10^{-5}$, with chosen coding parameters and decoding strategy, the CMD performance figures⁵ can be estimated.

1. Probability of CMD rejection

$$(nPe)^N = 9.8 \times 10^{-14}$$

2. Probability of spurious CMD

$$N[w(d)Pe^d] = 1.8 \times 10^{-42}$$

$$\text{where } w(d) = \frac{{}^n C_d}{\sum_{i=d}^n n C_i} (2^k - 1),$$

$$Pe = 10^{-5}, n = 56, d = 9, N = 4 \text{ and } K = 32.$$

3.4 On-board CMD system capabilities

3.4.1 Real-time CMD execution

The uplink CMDs sent from the ground are executed by the spacecraft sub-system immediately. Majority of them are real-time commands. For SROSS, 160 ON/OFF pulse commands and 15-data (each data is 16-bit long) commands are used.

3.4.2 Time-tag CMD operation

When the uplink CMD execution is to be delayed by a fixed time, the CMD is stored in the TC memory. The time delay information is uplinked as a second CMD, reception of which loads the TT CMD with a definite time delay, at the appropriate place in the TT CMD buffer, awaiting execution. The set time delay is continuously compared with a running reference on-board time (OBT) and the TT CMD is executed when the time matures. All CMD which are executable in real-time can be executed as TT CMD. A maximum of 16 TT CMDs can be stored at a time. The minimum and the maximum time delays that can be specified for any CMD are 4 seconds and 72 hours, respectively.

3.4.3 TC function CMD

These commands are used for internal functions in TC system; for example, to define time-delay value for TT CMD operation. Other commands in this group are related to enable/disable the software-based timer commands, software modules telemonitoring the TC memory contents, etc.

3.4.4 On-board command management

Pre-programmed CMD sequences can be executed with certain defined CMD execution. Mission-defined commands get executed with the actuation of certain events on board the spacecraft *i.e.*, spacecraft power on and the separation of launch vehicle and the spacecraft, automatic on-board command generation for switching ON/OFF the thermal heaters, for temperature control of certain critical sub-systems of the spacecraft.

3.4.5 PCM telemetry data acquisition

On-board time data and data relevant to thermal heaters are continuously acquired into the TC system from the telemetry system to operate the TT CMDs and for on-board CMD generation.

3.5 System description

The on-board TC system configuration block diagram for SROSS is shown in fig. 2.

3.5.1 Front-end demodulator

The front end receives the PCM/FSK CMD signal from the TC receiver. Two matched-band pass filter (BPF) chains follow the buffer (fig. 3). In each chain, the BPF is a 4-pole (roll off 24 dB/octave), and has 400 Hz BW, a compromise between in-band noise reduction and signal fidelity. The filter is realised^b using operational amplifiers. The filter output is followed by a diode to remove the negative half-cycles of the sub-carrier and also to ensure that around 500 mV base noise is cut-off. The signal is amplified with

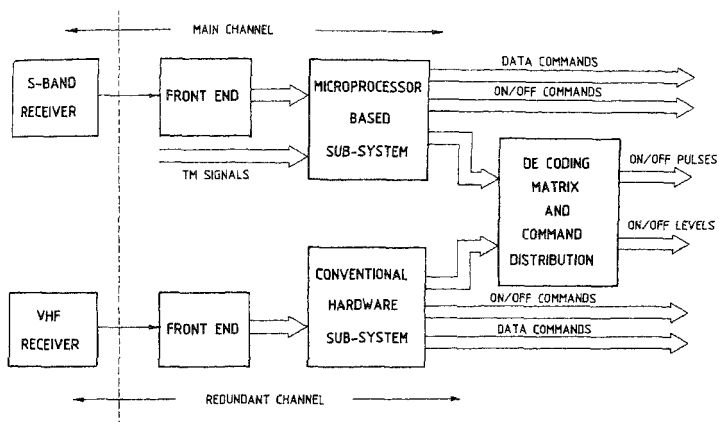


Fig. 2. SROSS TC system block diagram.

a gain, such that a minimum of 2-volt peak-to-peak signal from the TC receiver reaches the CMD threshold. The analog signal is converted to digital wave form. Digital integrate and dump is realised using counters. From both the chains the signal is ORED to have bit envelope detection. For each bit the integrate and dump counts are input to the CMD processing unit and also the redundant hardware decoder unit.

The TC receiver output specifications are:

CMD signal swing : 2 to 5 volts peak-to-peak

SNR : 0 dB at receiver O/P, BW=15 KHz

Max. baseline noise : 500 mV peak-to-peak.

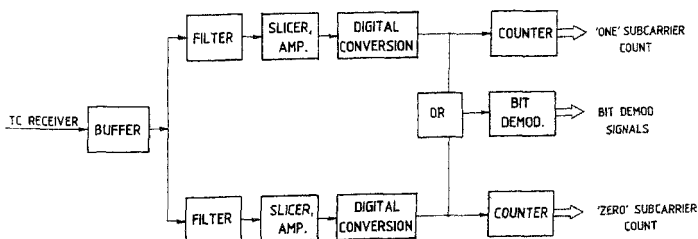


Fig. 3. TC system front-end block diagram.

3.5.2 Command processing unit

At the heart of the system is an RCA 1802, an 8-bit microprocessor-based CMD processing unit (fig. 4)⁷. The following functions are carried out using the software.

When the TC front end receives the CMD signal from the TC receiver, the CMD acquisition process starts; on every CMD data bit received, bit decision and bit storage are performed. After the CMD frame reception, CMD data verification and validation are done, to check the correctness of the CMD frame received. If the frame is not correct, it is rejected and processing starts for the next incoming frame; if correct, the frame is

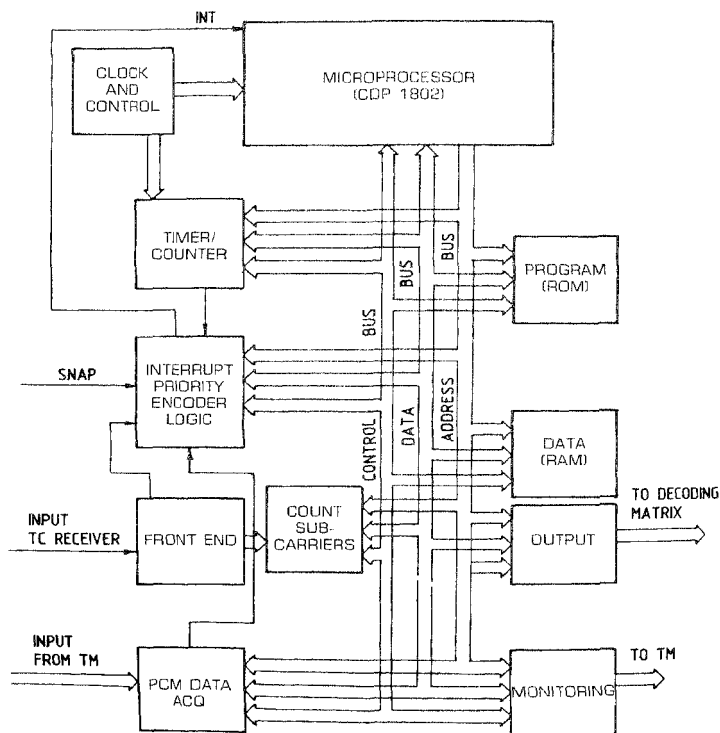


FIG. 4. Microprocessor sub-system block diagram.

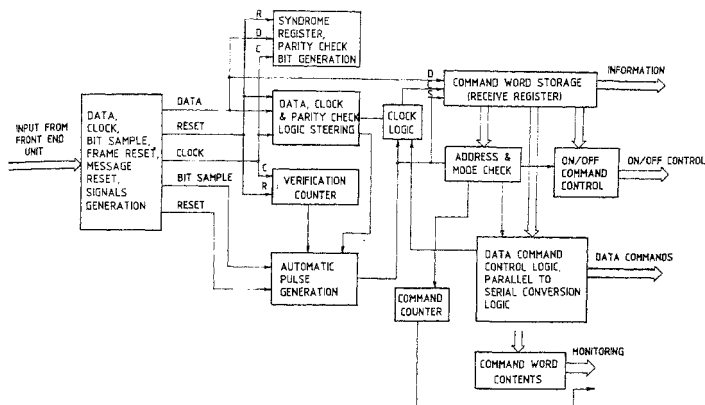


Fig. 5. Hardware decoder sub-system block diagram.

accepted and the remaining incoming frames are ignored. Spacecraft and decoder addresses in the CMD word are verified. Depending on the mode setting in the CMD word, the CMD information is used. In the real-time mode the CMD is executed by the spacecraft sub-system; in TT CMD mode the CMD is stored in the TC memory for execution at a later time, and under the TC function mode the assigned TC operation is performed.

All the other CMD functions listed in section 3.4 are executed by the software as and when required.

3.5.3 Redundant hardware decoder

To provide complete redundancy to real-time commands, flight-proven hardware version of the decoder is incorporated, which caters to commanding the spacecraft through VHF backup uplink chain. A separate front-end demodulator feeds the decoder. The command output is directly given to the command distribution unit (fig. 5).

3.5.4 Command distribution unit

Uplink command can actively be received and processed by the CMD processing unit and hardware decoder, but the CMD is routed through this unit for execution and distribution to the spacecraft sub-systems.

3.6 System software

The TC system software comprises different functional modules. Each module is structured in such a way that a definite set of them can perform a desired CMD function

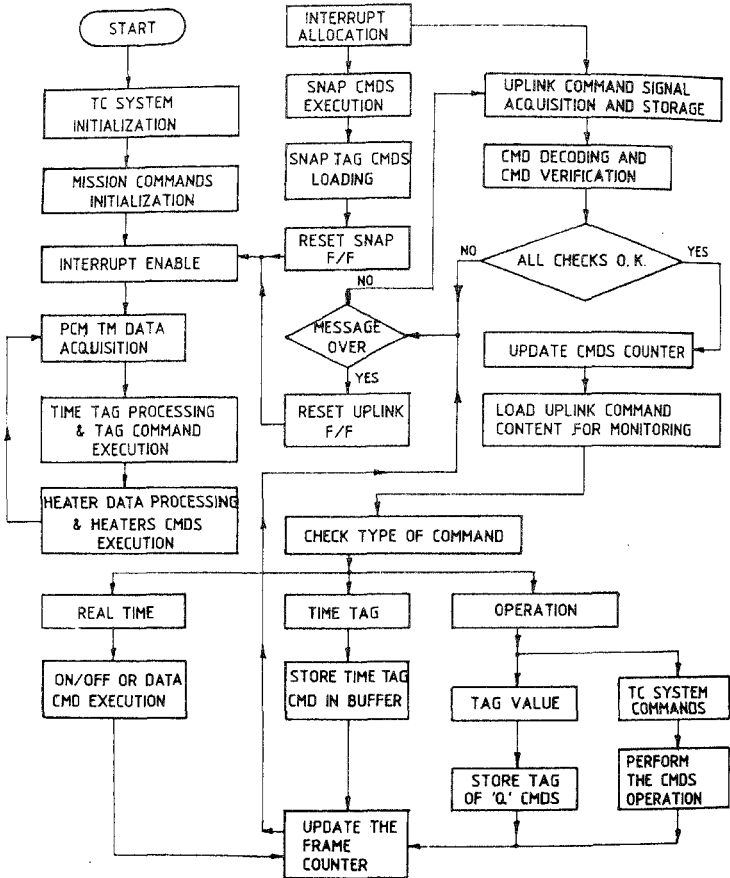


FIG. 6. TC software flow chart.

(fig. 6). The functions are carried out as and when required. The uplink CMD processing is given the highest priority. To start with, the main programme does the system and mission command initialisation, then goes into a continuous loop of PCM telemetry data

acquisition and analysis for time tag and on-board CMD generation until interrupted by the uplink CMD signal.

4. System performance results

The flight-worthy system is housed in a single package of dimension $165 \times 280 \times 150 \text{ mm}^3$. The system circuitry/multiplication sign is accommodated on six densely packed PCBs. The total weight of the system is 2.8 kg. The dc power consumption is around 400 mW.

The various on-board TC system performance parameters are monitored through analog and digital channels, allotted to the telemetry of the spacecraft. All the important

Table I

Sl. No.	Signal (r.m.s.)	Noise (r.m.s.) BW = 15 KHz	S+N (r.m.s.)	SNR db	No. of CMD frames transmitted	No. of CMD frames accepted	No. of bits in error	Bit-error rate (Pe)	Eb/No (dB)
1.	0.488 V	0.596 V	0.767 V	-1.74	2000 (1,12,000 bits)	1983	47	4.2×10^{-4}	+17.01
2.	0.490 V	0.500 V	0.700 V	-0.18	2000 (1,12,000 bits)	1998	02	1.79×10^{-5}	+18.57
3.	0.485 V	0.397 V	0.630 V	+1.74	2000 (1,12,000 bits)	2000	00	—	+20.49
4.	0.826 V	1.190 V	1.445 V	-3.17	2000 (1,12,000 bits)	1865	138	1.23×10^{-3}	+15.58
5.	0.828 V	1.197 V	1.470 V	-3.20	2000 (1,12,000 bits)	1911	91	8.13×10^{-4}	+15.55
6.	0.828 V	0.996 V	1.288 V	1.61	2000 (1,12,000 bits)	1998	02	1.79×10^{-5}	+17.14
7.	0.833 V	0.996 V	1.280 V	-1.69	2000 (1,12,000 bits)	1996	04	3.57×10^{-5}	+17.06
8.	1.245 V	1.195 V	1.708 V	+0.36	2000 (1,12,000 bits)	1811	200	1.79×10^{-3}	+19.11
9.	1.118 V	0.996 V	1.503 V	+1.00	2000 (1,12,000 bits)	1997	03	2.68×10^{-5}	+19.75
10.	1.241 V	0.998 V	1.573 V	+1.89	2000 (1,12,000 bits)	1996	04	3.57×10^{-5}	+20.64
11.	1.241 V	0.895 V	1.538 V	+2.84	2000 (1,12,000 bits)	1999	01	8.93×10^{-6}	+21.59

$$\text{Bit-error rate } Pe = \frac{1}{2} e^{-\frac{Eb}{2No}} \text{ for non-coherent FSK}$$

$$Eb/No = 10 \text{ Log } 10[-2 \log_e (2 \times Pe)] \text{ dB (Theory)}$$

$$Eb/No = S/N \times \frac{\text{Noise BW}}{\text{Bit rate}} = S/N + 18.75 \text{ dB (Experimental)}$$

parameters are monitored on dedicated channels for continuous performance evaluation of the system.

The system is thoroughly tested for long-duration operation. The system performance is evaluated and verified for the intended application, specially to check the reliability of the system, in simulated space environment. The system is subjected to various environmental qualification tests *i.e.*, vibration, shock, hot and cold, long-duration thermovacuum tests, etc., according to the procedure and standards laid down by the quality assurance. In all test conditions, the system performed quite satisfactorily.

For error-free CMD performance estimation, a long-duration bit-error measurement programme is run on the actual system, by introducing a simulated-noise signal along with PCM/FSK CMD signal. Except for a few CMD frame rejections actual spurious CMD execution was never observed. A sample of bit-error measurement is tabulated in Table I. Based on the in-orbit experience of the APPLE satellite on-board TC system CMD performance (with similar BCH coding scheme *i.e.*, 31, 16, 7 BCH code), where more than one lakh commands were executed and no single spurious CMD execution or rejection was observed, it is assumed that the system performance will be satisfactory during the in-orbit application.

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