A Multiple-Rate Command System

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The impact of a multiple-rate command capability on the present end-to-end ground spacecraft command system has been studied. Limitations in the present command system include a maximum average command word (71 bits or less) transfer rate of 1 word per second and a mean time between failure of 13 hours for the ground portion of the system. Command rates are currently set by end-of-mission (EOM) requirements. Adding a multiple-rate command capability to the present spacecraft command subsystem would result in more reliable flight computer updates during mission phases which could support higher than EOM command rates. During non-catastrophic spacecraft anomalies, commanding could be made more reliable by decreasing the command data rate below EOM requirements. In addition, a flexibility of command rate could be used to optimally apportion command activity between the 26-m and 64-m antenna Deep Space Stations when multiple-spacecraft missions are in progress. The increase in hardware cost necessary to implement a multiple-rate command capability is estimated to be less than 1% of that of current command flight hardware.

I. Introduction

This report describes the results of an investigation into the overall ground/spacecraft command system. The investigation was directed to increasing the ability of the command system by incorporating a multiple-rate capability. The present command system with its capabilities and limitations is outlined. This is followed by a discussion of the impact and benefits which a multiple-rate requirement would have on the system. The impact is shown to be small, but the return in improved utilization would permit greater command traffic and complexity at less cost than the present system expanded to meet the same requirements of traffic and complexity.

II. The Commanding of Spacecraft

Experience over the last decade has shown that a spacecraft's mission is beset with unpredictability, targets of opportunity, and extensions to the prime mission which are most easily handled by remote control. The ground-based command system presented in this report implements this remote control and thus provides for optimum use of the spacecraft in flight. By combining the technical expertise, data processing power, and decision making capabilities of a ground support team with a reliable and efficient command link, both the operation of the spacecraft and the usefulness of data returned by the spacecraft are improved. An overall view of the present system is provided to furnish a base for the discussion of one improvement in the system, specifically, the capability of commanding a spacecraft at any of several predetermined bit rates consistent with performance requirements and mission phase.

Unmanned planetary missions in the past and through Mariner Jupiter/Saturn 1977 (MJS'77) have not had a major requirement for more than one command bit rate. This, however, is not the case starting with Mariner Jupiter/Uranus 1979 (MJU'79). The third section addresses some solutions to this requirement. The advantages of this improvement, called a Multiple-Rate Command System (MRCS), extend beyond the requirements of the MJU'79 mission. An MRCS would provide improvements in the overall reliability and operations costs on all missions.

III. The Present Command System

The present command system is a combination of special-purpose hardware, computing equipment, software, and organizations within the laboratory responsible for the design, maintenance, and use of the system.

A. Functional Description

Before attempting to delineate the parts of the system, an overview of the functional elements and requirements will serve as a basis upon which to build the description of the system. Figure 1 shows the functional elements and their relationships. General command requirements and sequences are created by a Mission Planning Team (Box 1). This information, combined with the present state of the spacecraft, is used to generate the command strategy, that is, the exact sequence of commands required to change the present state of the spacecraft into that required for the mission plan (Box 2). In real time, the hardware of the Multimission Command System is configured (Box 3) to support a specific mission. The configuration and subsequent performance are monitored (Box 7) to insure usability. Also in real time, the commands generated in Box 2, above, are translated into sequences of bits (digital patterns) (Box 4), which are used to modulate the ground station transmitter (Box 6). On board the spacecraft, received commands are checked for transmission errors, decoded, executed, and the new state of the spacecraft is telemetered back to the ground (Boxes 8 and 9). Telemetry data and ground system monitor information are used to insure that the commands have been transmitted and received correctly (Box 5). The telemetry is also used in non-real time as an input to the next command sequence generation (Boxes 1 and 2). Emergency, nonstandard, and rapid response to new conditions require complex checking, feedback, and feedthrough paths within the command system. These complex paths, however, do not change the fundamental functions presented above.

B. Organizational Structure

The organizational structure of the present system is presented in Tables 1 and 2. Table 1 expands upon the functional requirements showing the relationship between the users, designers, and operators of the equipment. The first column provides a reference to the functional diagram of Fig. 1. The second lists the organization that is the primary user of that functional element. The next two columns describe the special-purpose hardware required for the function and organization responsible for its design. Similarly, the general-purpose computing equipment, the software for it, and the design organization are listed in the next three columns. The last column lists the organization responsible for operating the equipment.

Table 2 uses the information of Table 1 rearranged in terms of the four major functional installations within the command system. These are presented in the center of the table and are:

(1) Mission planning, command generation, and command simulation.

(2) Mission computing and control.

(3) Deep Space Network and network control.

(4) Spacecraft command equipment.

Flanking this listing are the organizations responsible for the development and for the operations of each installation.

C. Present Implementation and Capabilities

The following discusses, in general terms, the equipment used by the present command system to meet the functional requirements. It is organized along the equipment boundaries rather than the previously described functional boundaries.

1. Ground communications. The communications of all command-related information between the control installation (Mission Control and Computing Center (MCCC)) and the Deep Space Station (DSS) is over the high-speed data line (HSDL). The data are sent serially in blocks of 1200 bits at a rate of 4800 bits/s. Block throughput rate for this duplex channel is 99.5% (Ref. 1). This HSDL bit rate, however, does not adequately describe the transfer rate of commands through the high-speed data line. When the block structure is examined in detail (Refs. 2 and 3), it is seen that the maximum command word rate, for commands of 71 bits or less, is about 1 per second. For present bit rates this is more than adequate. However, for command element radiation times approaching 1 command element per 2 seconds, serious difficulties may be encountered.

The overall channel is protected against errors within the block. The probability of accepting a bad block is less than 2×10^{-10}. This is provided by a 33-bit polynomial check word sent as part of each block. Line outages are defined as a minimum of 10 blocks in error (Ref. 4). These outages are protected against by a feedback path between the DSS and MCCC. The mean-time-to-failure of this type of outage has been measured at 4.76 hours. In addition, 87.5% of the outages have a duration of less than or equal to 1 minute (Ref. 4). Therefore, the probability of an interruption exceeding 1 minute is 6.25×10^{-4}.

2. Command Modulator Assembly. The Command Modulator Assembly (CMA) is a special peripheral for the Telemetry and Command Processor (TCP) (Ref. 5). The CMA provides the interface between the TCP and the exciter through which command bits are sent. In addition, the CMA sets and checks the operation of itself, reporting to the TCP both correct and incorrect operations. Because of the multimission requirements, the CMA has been designed to modulate the exciter with an FSK or PSK waveform (Ref. 6). Each of these options is controlled from the TCP. The selection is communicated from mission operations via the Network Operations Control Center (NOCC) over the HSDL.

Each command bit is verified both when received by the CMA and when sent to the exciter. If a descrepancy should occur at any time during radiation (bit value, frequency, modulation index, exciter/transmitter operation, etc.), the CMA or the TCP will cause commanding to abort. By this process, invalid commands are not allowed to reach the spacecraft decoder. The abort condition is also reported to the other elements of the command system so that corrective action may be taken. In addition to the automatic abort actions, a manual abort may be performed. This permits aborting valid but incorrect commands.

The CMA can operate at rates up to 1000 bits/s to a resolution of 1% or less (10 μs in period). The resolution in setting other frequencies associated with modulation is 0.1 Hz from 1000 Hz to 1 MHz.

The measured reliability and repairability figures taken from continuing performance studies are: mean time between failures (MTBF) = 196 hours, mean time to repair (MTTR) = 14.5 minutes. These figures include the reliability of both the TCP and CMA (Ref. 7). A further constraint associated with the CMA is that the bit rate does not exceed 1/20 of the subcarrier frequency. This constraint is imposed by the subcarrier frequency validation circuitry (Ref. 8).

3. Telemetry and Command Processor. The function of the Telemetry and Command Processor (TCP) for command is to accept command bit patterns through the HSDL, check and reject data corrupted by transmission errors, set and check the operation of the CMA, send command words to the CMA at the proper time, notify MCCC of the radiation or abort of each command element, and maintain, under control of MCCC, a stack of commands identical to those contained in the command queue at MCCC. If the HSDL should fail, commands can be entered into the TCP manually.

With the TCP processing command data only, bit rates as high as 32 bits/s have been successfully demonstrated. When processing telemetry, the maximum bit rate is limited to about 8 bits/s.

The reliability information given above for the CMA applies to the TCP as well. (MTBF = 196 hours; MTTR = 14.5 minutes.)

4. Command Detector Unit. The following describes a digital Command Detector Unit (CDU) of the Viking type (Ref. 9). This type of device has been accepted by the MJS'77 Project and will probably be accepted by the MJU'79 Project. The digital CDU acquires both subcarrier phase and bit synchronization by maximum likelihood detection of digital correlations performed on the input signal. The phase tracking of the signal is also accomplished digitally. As presently designed, the CDU demodulates a signal whose subcarrier is fixed at 512 Hz and whose bit rate is selectable at the time of CDU manufacture at 1 Hz or from 2 to 256 Hz in even increments.

A bit error rate of 1×10^{-5} is selected as a threshold value. At this threshold the probability of false acquisition is 1×10^{-4}, while the probability of false out-of-lock is 1×10^{-5}. For a single command of the Viking type, the probability of incorrect execution is 10^{-6} and the probability of failure to respond is 10^{-3}. For a Viking block of 50 words the probabilities are 5×10^{-5} and 5×10^{-2}, respectively (Ref. 10).

5. Central Computer and Sequencer Subsystem. The spacecraft Central Computer and Sequencer Subsystem (CC&S) performs several activities in the command chain. The detected bits of a command message are received serially from the CDU, tested for start of message, and assembled into words. The words are decoded, checked for parity, and routed to the appropriate spacecraft subsystem. A delay of 10 bit times permits the aborting of a command after it has been received and decoded. The abort is indicated by a loss-of-lock in the CDU.

The speed of the present CC&S, with its flight software, permits a decoding bit rate of 50 Hz maximum (i.e., provided the CC&S does no other processing) and a typical decoding rate of 20 Hz. A change in the flight software philosophy could double this rate (Ref. 11).

6. Mission Control and Computing Center. The Multimission Real-Time Command System accepts the command data as a file and communicates these data to the appropriate DSS. Responses from the DSS are used to verify that commands are sent in a proper and timely way. Full control of the command operation is maintained by the command operator. The Mission Control and Computing Center (MCCC)–DSS software maintains a feedback control of the DSS command subsystem via the HSDL.

Mission Control and Computing Center facilities are designed to handle nine DSS/TCPs simultaneously. Each DSS is handled through a communicator having a capacity of 3000 queue elements (71 bits). The functions within the MCCC command system can be processed at rates greater than 1000 bits/s (Ref. 4).

The reliability and maintainability of the MCCC command system have been measured for a period greater than 1.5 years. These measurements show that the present MTBF is 23 hours and the MTTR is 9 minutes (Ref. 12).

7. Other elements. The Flight Data System (FDS), Network Operations and Control Center, and the ground telemetry processing do not have a direct impact upon the multiple-rate capabilities of the command system and will not be amplified upon in the present report. Table 3 presents a summary of the above information.

IV. Multiple-Rate Command System

Certain improvements in the performance of the command function can be obtained by permitting the bit rate of commands to be adjustable in flight. Such a system has been investigated for feasibility and applicability. The proposed Multiple-Rate Command System (MRCS) would permit the radiation and reception of commands at several rates to one spacecraft. The choice of rates would be predetermined, but the selection would be done in real time during the flight.

The CDU is the only component in the total command system that prevents the immediate testing and adoption of MRCS. Philosophically, the changes required to make the CDU compatible with MRCS are small. Likewise, the hardware required represents less than a 1% increase in the cost of the flight equipment. Before outlining the changes required in the CDU, a brief review is presented of the benefits that MRCS would provide.

A. Benefits Obtainable With MRCS

The benefits obtainable from MRCS accrue from three sources: (1) increased rates over those of end-of-mission (EOM) limitations, (2) decreased rates under those usable throughout the mission, and (3) the flexibility in selecting rates as a function of resources.

1. Benefits from increased rates (above normal EOM). Considering the overall performance of the command system, higher rates will increase the probability of completing a command sequence. This benefit arises from the moderate reliability of the ground command system. Measurements to date of ground system reliability show an MTBF of about 13 hours (Ref. 11). Using an exponential reliability function (Fig. 2), this represents a probability of completing an 8-hour command sequence of 54.0%, for 4 hours of 73.5%, and for 2 hours of 85.7%. Assuming for the moment that the 4 to 1 range in rates is compatible with the space link performance, that is that the signal-to-noise ratio (SNR) does not drop below the threshold, the probability that a command sequence could be completed in an 8-hour shift is 54% at the 8-hour rate, 92.9% at the 4-hour rate, and 99.96% at the 2-hour rate. The above figures assume an idealized system operation where repairs require negligible time. The figures, however, do serve to place an upper bound upon the improvement and to indicate the relative improvement resulting from shorter command sequence times. Furthermore, at 1 bit/s, 8 hours of command represents 28,800 bits. For on-board computers with 18-bit words, this would represent a 1600-word update. Such an update is typical for a Mariner class spacecraft.

MJS'77, a typical spacecraft of the next era, contains 3 computers with 4000 words of storage each (Ref 13). Limiting a worst case update to 80% of the available storage and excluding the loading of the back-up computers, the maximum command sequence time at 1 bit/s would be about 48 hours. Continuous operation for 48 hours has only a 2.5% probability of occurring. At a command rate of 4 bits/s, the time would be 12 hours and the corresponding probability of completing the command update without ground system failure would be 39.8%. Commanding at 8 bits/s would result in a 6-hour sequence, which could be repeated in a 12-hour pass, yielding an 86.3% probability of completion.

An alternate view of the use of the system would be to limit command sequences to those of a length such that the probability of completion exceeds some value. For the following discussion, 80% has been used as the minimum allowable probability of completion. At the MTBF of 13 hours, this yields sequences no greater than 2.90 hours. Table 4 gives update sizes versus bit rate for this time (80% of 12,000 words equals 9600 words). If such a sequence were sent twice, the reliability would be 96% and take 5.8 hours. For three transmissions, the reliability would be 99.2%, and the time would be 8.7 hours. This, again, neglects repair time, but for the present system 98% of the repairs would be completed in less than 1 hour, thus increasing the overall time required for the double transmission to less than 6.8 hours and the triple transmission to less than 10.7 hours. Both are well within a 12-hour pass.

The command acquisition time is fixed at 90 bit times. Thus for 1, 2, 4, 8, and 16 bits/s this results in 90, 45, 22.5, 11.25, and 5.625 seconds, respectively. The MJS'77 Project has specified a commanding sequence in which the CDU lock is broken after each block of about 1000 bits (Ref. 13). If such a strategy is adopted, it will increase the overall active command time required (i.e., the time that the system must be up). This results in a corresponding reduction in probability of completion. For any specific mission with values of ST_B/N_0 at the spacecraft and commands sent in blocks of N bits, a series of curves could be generated to provide an optimum strategy at each point in the mission. Aside from the above outline of such a process, the generation of such curves is outside the scope of this report.

By completing a command sequence with a high probability in less than 8 hours, a second shift would be obviated. The staffing for command costs about $160,000 per year for a shift of 8 hours, 7 days per week (Ref. 14). For long-term missions such as MJU'79 (11 years), this reduction in operations staffing can result in large savings.

The number of commands per unit time has increased as missions have become more complex. With continued increasing complexity, longer missions, and expanding options within a mission, this increase should continue. The increased traffic places a heavy load upon the DSN. By 1977, 16% of the tracking time will be required for command. This figure excludes extended missions and, as a result, is probably low. Furthermore, in these initial calculations, no attempt has been made to include the effects of view period. This also may result in a value too low for some periods. The ability to select a bit rate compatible with mission phase from a set with adequate range will aid in keeping the net loading within bounds.

2. Benefits from decreased rates (below normal EOM). The benefit achievable from decreased bit rates comes mostly from the increase in received SNR over the command channel. The most outstanding benefit of this type is in the event of a spacecraft emergency where commandability can be increased.

Such a condition has been encountered in the design of the Viking 1975 mission (Ref. 15). At superior conjunction with the 26-m, 10-kW subnet and the low-gain antenna 30 deg off axis (a condition possible through loss of attitude sensor lock), the required bit rate to maintain a bit error rate threshold of 1×10^{-5} is less than the fixed 4 bits/s.

MJS'77 will require the 64-m, 100-kW station at its 16-bit/s rate to command out of trouble at Saturn encounter and beyond (Ref. 14). With the present design of the MJU'79 mission, at Uranus encounter and during probe insertion, the spacecraft will be commanded to an attitude where further command must be at 1 bit/s to be reliably accepted. This condition occurs with the 64-m subnet at 100 kW.

With the exception of MJU'79, no provision has been made to avoid these difficulties. The lower bit rates of MRCS would improve the commandability in these cases. MJU'79, recognizing the extent of the problem, is requiring that at least 2 rates, 1 and 16, be available.

3. Benefits from the flexibility of bit rate. The flexibility in selecting bit rate delivers benefit in two areas: (1) it permits the optimization of the entire command link over the mission in terms of command reliability (a combination of link performance and ground system reliability), and (2) it permits the allocation of command activity between the two subnets (26 and 64 m).

B. Changes Required to Support MRCS

In this section only those changes required to test and apply MCRS will be discussed. This set of changes may not result in the most efficient MRCS, but does result in an MRCS with a lower overall system impact. The final section will discuss briefly those areas which require further study and which may result in a more optimum system.

1. Changes required of the ground system. No hardware changes are required for the ground command system to be able to support MRCS up to a rate of 16 bits/s. However, procedures must be developed to permit the changing of rate during a pass, monitoring this activity, and verifying it. This requires the coordination of activities between Mission Operations System (MOS) and NOCC. The DSS is transparent to these activities.

2. Changes required of the flight system. The changes required of the flight system are of both the hardware and software type.

Two elements of the command subsystem hardware are affected. First, the CDU rate selection must be made flight programmable. Second, an interface from the CC&S to CDU must be developed to activate the rate change.

The change in flight software involves only a small expansion to handle the CDU interface. It does not represent a change in philosophy. This modified on-board command subsystem is shown schematically in Fig. 3. Command modulation delivered from the Radio Frequency Subsystem (RFS) is processed by the digital CDU. The demodulated command bits, with indicators showing CDU status, are sent to the CC&S where the commands are decoded. When a rate selection command is recognized, the pertinent information is sent back to the Rate Selection Storage Register through an appropriate interface. Data from the Rate Register are communicated in parallel with the CDU where it controls timing signals.

3. Use of MRCS. The spacecraft command operation can be broken into two subtypes: (1) discrete commanding, and (2) on-board computer updating. Discrete commanding is characterized by a low density of command words; therefore, no appreciable gain can be obtained by increasing the bit rate. However, computer updates are characterized by high command density and would benefit from higher bit rates.

A command sequence involving a computer update would probably consist of: (1) acquisition of command uplink at lowest rate, (2) transmit rate change command for higher rate as a discrete command, (3) break bit sync lock and reacquire higher bit rate, (4) transmit update at high rate, and (5) transmit rate change command for lowest rate. In addition, the CC&S would be required to monitor command activity. If no activity occurred within a given period of time, the CC&S would command the CDU to the lowest rate.

This sequence of operations would insure optimum commandability at all times excluding spacecraft emergency, and would provide for greatest commandability in the event of a spacecraft emergency.

C. Other Approaches to MRCS and Their Impact

The approach discussed so far has assumed that the CDU resides within a flight command system which includes the CC&S. While this simplifying assumption is valid for JPL spacecraft, it may not be so industry-wide.

Two approaches have been considered for a "stand-alone" CDU which would meet the MRCS requirements. The first includes, essentially, a limited decoder which would process a command message header and set its operation for the proper bit rate. The second approach would determine, without the aid of a special header, the bit rate being transmitted and lock to it.

Analysis of these two options is still in progress; thus a complete and fair comparison of the two approaches cannot be made at this time. Preliminary studies, however, indicate that the first of the two approaches (i.e., a CDU containing a limited decoder) would require changes in the MCCC, DSN, and NOCC hardware and/or software. This would be in addition to those procedural changes required of the base system described in Subsection IV-B. Neither of these changes would be required for the second type of "stand-alone" CDU.

V. Conclusions

Multiple-rate commanding is compatible with the major portion of the present command system. It would provide advantages in system reliability, network loading, and operations costs. Ground system effective reliability can be increased from 2.5 to 86.3% for a worst-case on-board computer load. By permitting optimum rate commanding through either the 26-m or 64-m subnets, the availability of the total network is increased. The shorter command periods will, further, reduce operations costs, a significant effect for the long-term missions of the next era. These advantages can be obtained without extensive and costly changes to the present spacecraft/ground command system.

The work in process analyzing the above candidates for performance and total system impact will lead to an optimum on-board CDU. By considering the total system impact, such a CDU will be optimized in the global sense rather than in the narrow confines of its discipline.

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Table 1. Functional delegation to organizations

Function	User organization	Special hardware	Development organization	Computers	Software	Development organization	Operation organization
1. Mission planning	Project Office (200) Project Engineering Division (290)	None	—	360/75 nonreal time (Mission Computing Facility (MCF))	Sequence of events	Flight Applications Programming Section (915)	Mission Computing Section (918)
2. Generate command strategy	Project Office (200) Project Engineering Division (290)	None	—	1108 nonreal time (Scientific Computing Facility (SCF)) 360/75 real and nonreal time	Assembler for on-board computer command generation simulation Sequence generation Command generation and simulation	Data Systems Engineering Section (916), (292), (361), (363), (340) Flight Applications Programming Section (915)	Science and Engineering Computing Section (914) Mission Computing Section (918)
3. Configure ground system	DSN Systems Engineering (430) Space Flight Operations Section (295)	Network Control Systems—Computer Network (NOCC)	DSN Data Systems Development Section (338)	Modcomp Sigma 5 [real time] (Network Data Processing Area (NDPA))	NCS Command System NCS Support Program	DSN Data Systems Development Section (338)	DSN Facility Operations (422)
4. Translate commands	Project Office (200) Space Flight Operations Section (295)	None	—	360/75 real time (MCF)	Real-Time Multimission Command System—Command Translator	Data Systems Engineering Section (916) Flight Applications Programming Section (915)	Mission Computing Section (918)
5. Process telemetry (for command)	Project Office (200) Project Engineering Division (290) Space Flight Operations Section (295)	DSN-receiver Subcarrier demodulator Symbol synchronizer Data decoder Block decoder Ground communications equipment (HSDL)	R.F. Systems Development Section (335) DSN Data Systems Development Section (338)	Interdata 4 (Data Decoder Assembly (DDA)) SDS 920 (TCP) 360/75 real time (MCF)	Data Decoder Program TCP Program Real-Time Multimission Telemetry System	DSN Data Systems Development Section (338) DSN Data Systems Development Section (338) Flight Applications Programming Section (915)	DSN Facility Operations (422) Mission Computing Section (918)
6. Transmit commands	Space Flight Operations Section (295)	Transmitter and modulator Antenna Antenna Control Processor Command Modulator Assembly Ground communications equipment	R.F. Systems Development Section (335) DSN Engineering Section (332) DSN Data Systems Development Section (338)	SDS 910 (Antenna Pointing Subsystem (APS)) Telemetry and Command Processor (SDS920) (TCP) 360/75 Real-Time System (MCF)	Antenna Pointing Subsystem Program TCP Program Real-Time Multimission Command System	DSN Data Systems Development Section (338) Data Systems Engineering Section (916)	DSN Facility Operations (422) Mission Computing Section (918)

Table 1 (contd)

Function	User organization	Special hardware	Development organization	Computers	Software	Development organization	Operation organization
7. Monitor ground system (see No. 3 (NCS))						DSN Systems Engineering (430)	
8. Process commands	Project Office (200)	Spacecraft radio Command Detector Unit Modulation Detector Assembly (MDA)	Spacecraft Radio Section (336) Spacecraft Telecommunications Section (339)	On-board control computer (CC&S) On-board data computer Flight Data System (FDS) Guidance and control computer (APS)		Spacecraft Computer Section (361) Spacecraft Data Storage Section (363) Guidance and Control Division (340) System Design and Integration Section (292)	

Table 2. Installations versus organizations

Development organization	Functional installation	Operating organization
Data Systems Engineering (916) Flight Applications Programming (915) Systems Design and Integration (292) Spacecraft Computers (361) Spacecraft Data Storage (363) Guidance and Control (340)	Mission planning Command generation Command simulation	Mission Computing (918) Science and Engineering Computing (914)
Data Systems Engineering (916) Flight Applications Programming (915)	Mission computing and control	Mission Computing (918)
DSN Data Systems Development (338) R.F. Systems Development (335)	Deep Space Network and network control	DSN Facility Operations (422)
Spacecraft Radio (336) Spacecraft Telecommunications (339) Spacecraft Computers (361) Spacecraft Data Storage (363) Guidance and Control (340)	Spacecraft command equipment	Space Flight Operations (through command link) (295)

Table 3. Performance characteristics of system elements

Element	Throughput	Reliability			Flexibility	Error rate	Accuracy
		MTBF	MTTRS	Redundancy			
High-speed data line (HSDL)	4800 bits/s 4–1200 bit blocks/s 6 command words/block ≈ 1 command word/s (includes feedback checking) Block throughput rate 99.5%	4.76 h for outages of 10 blocks or more 38 h for outages of 1 min or more	14.8 m $\alpha = 0.9958$*	Partial or full	N/A	From 1×10^{-5} to 5×15^{4} bit error rate From 3×10^{-4} to 5×10^{-3} block error rate 1×2^{-33} undetected bit error rate	N/A
Command Modulator Assembly (CMA)	1000 bits/s	196 h (includes TCP)	14.5 m $\alpha = 0.9988$	Partial or full	Mode (1) Frequency shift keying (FSK) (2) Phase shift keying (PSK) (3) Direct carrier phase modulation (4) PSK-PN (sync) (5) PSK-Manchester II coded	Theoretical (predicted) bit error rate 1×10^{-6}	
					Subcarrier 100 Hz to 1 MHz		0.1-Hz resolution
					Sine or squarewave data rate 1 bit/s to 1 kbit/s		10-μs resolution in period above 1 bit/s
					Modulation voltage 50 to 800 mV peak		3.14-mV resolution
					FSK frequency 100 Hz to 1 MHz		0.1-Hz resolution accuracy is tied to station reference frequency
Telemetry and Command Processor (TCP)	32 bits/s no telemetry 8 bits/s telemetry	196 h (includes CMA)	14.5 m $\alpha = 0.9988$	Partial or full	Programmed for multimission application	N/A	N/A

Table 3 (contd)

Element	Throughput	Reliability			Flexibility	Error rate	Accuracy
		MTBF	MTTRS	Redundancy			
Command Detector	256 bits/s	—	—	Full	1 to 256 bits/s (even rates)	Bit error rate at threshold, SNR + 10.5 dB, 1×10^{-5}. Acquisition Failure 1×10^{-4}. False out-of-lock 1×10^{-5}. Single command. Incorrect execution 1×10^{-6}. Failure to respond 1×10^{-3}. 50-word block commands. Incorrect execution 5×10^{-5}. Failure to respond 5×10^{-2}.	N/A
Central Computer and Sequencer (CC&S)	50 bits/s command decoding only 20 bits/s shared tasks Doublable with a change in flight software	—	—	Full	Fully programmable	N/A	N/A
Mission Control and Computing Center (MCCC)	>1000 bits/s	24 h	9 min $\alpha = 0.9932$	Partial or full	Fully programmable	N/A	N/A
Flight Data System (FDS)		—	—	Full	Limited format selection	N/A	N/A
Network Operations and Control Center (NOCC)	Rate change confirmed within 5 min—manual (Block II–Block III)				N/A	N/A	N/A

$$^{*}\alpha = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = \text{uptime ratio}$$

Table 4. Bit rate versus update size

Bit rate, bits/s	Approximate words in 2.90 h
1	580
2	1160
4	2320
8	4640
16	4280
32	18560
64	37120
128	74240

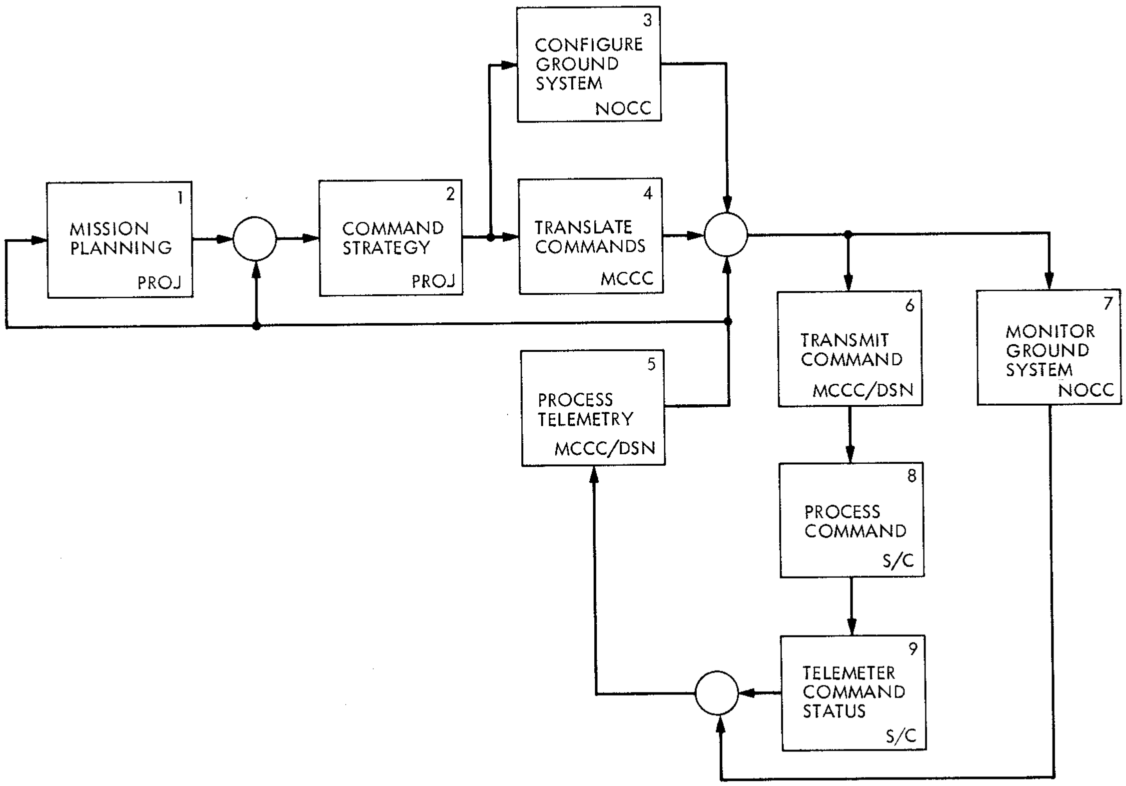

Fig. 1. Command System functional block diagram

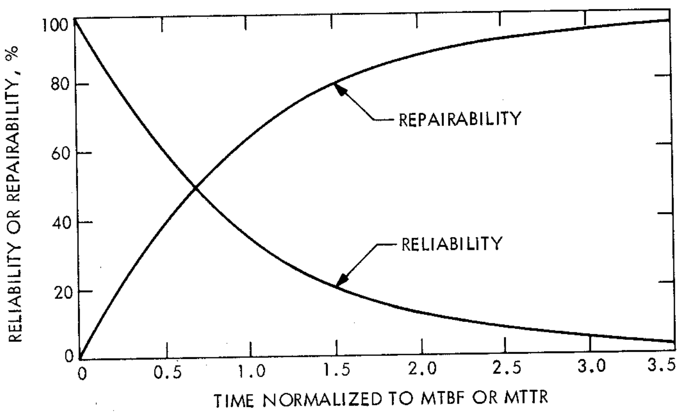

Fig. 2. Reliability and repairability vs normalized MTBF and MTTR

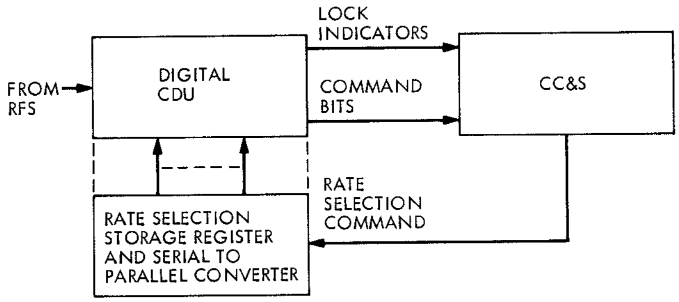

Fig. 3. Block diagram of MRCS on-board command subsystem