PROCESSING COMMANDS FOR GEOSTATIONARY SATELLITES

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Summary. This paper discusses command techniques that are employed for weather and communication satellites. The introduction describes the essential requirements for a command system. Detection of the baseband signal is analyzed with error budgets assigned to the command receiver. Subsequent discussions consider the command processor, low power, decrypters, critical commands, bus supply, remote command distribution, and redundancy. Finally, the command function in an operational spacecraft is presented.

Introduction. The spacecraft command system under consideration is essentially typical of that required to support launch and station keeping of weather and communication satellites. It is characterized by command baseband signal structure, bit error performance, command execution strategy, and control services to be provided to the spacecraft.

Figure 1 shows the required elements. The antenna feeds the modulated RF carrier to the receiver where the command message baseband is detected and routed to the bit detector. The bit detector reduces the baseband to binary digital data for subsequent decoding by the command processor with a resulting output to the using spacecraft subsystem. Outputs are typically pulses of relatively large amplitude, such as 28 volts to provide noise immunity, or relay contacts that are appropriately switched.

The command baseband signal structure generally differs with each satellite program depending on the customer. There are established standards for the Air Force Satellite Control Facility and for NASA, preferred structures for commercial customers who have some investment in ground stations, and designers choice for emerging customers. The signal structure falls into the category of PCM/FSK/AM/FM. Basically, this translates to a command baseband that employs frequency shift keying of two frequencies that represent logic one and logic zero with bit clock amplitude modulated on those frequencies. This baseband is then frequency modulated on the uplink RF carrier. Command systems have successfully used this basic structure. Other programs have added a third tone, with or without bit clock amplitude modulation, to provide for a command preamble or an execute command independent of the logic one and logic zero data bits. The digital structure of the baseband, which is usually PCM-NRZ or PCM-RZ, must of course, contain sufficient command message bits to encompass the number of commands required by the spacecraft. Additionally, bits are often required for command processor address when more than one processor is used, for parity check of the received command, and for accompanying instructions.

A specific example illustrating this discussion is shown in Figure 2. As can be seen there, the basic two tone signal is amplitude modulated at the bit rate, the logic zero tone is used for introduction to establish bit clock in the spacecraft bit detector, a bit transition is used to flag data bit start, and twenty bits are used for command message. Continuing transmission of the zero tones provides for sending subsequent commands without the need for repeating the introduction. An address implies more than one spacecraft processor.

Detection of the command message with low error probability and execution without error is the prime requisite of the command system. This problem involves a ground station effective isotropic radiated power and a space geometry imposed path loss that together dictate the minimum flux density available at the command antenna. Spacecraft design involves establishing antenna gain, line losses, receiver noise figure, and post detection processes to achieve the desired bit error rate. The goal is to avoid receiving false commands at the command processor and to have a high probability of successful command execution.

The command execution strategy focuses most importantly on the need to avoid execution of an unwanted command. To this end, an echo check of the transmitted command is required via spacecraft telemetry before an execute command will be sent. This load, verify, and then execute operation is not imposed by spacecraft hardware, but is part of operational discipline.

The command to execute a verified command message may be accomplished by using a third unmodulated tone as part of the baseband signal structure or by using part of the command message word. The latter concept, vector execution, uses some of the message bits for instructions to either store the accompanying command, or execute the previous command. Vector execution has an intuitive advantage in dispelling the uneasiness associated with the uncertainty of unwanted signals looking like the execute tone. For spacecrafts that use an on board decrypter to process ground encrypted commands vector execution is required because decrypters, located between the bit detector and message processor of Figure 1, are digital devices.

Control services to the spacecraft subsystems are often tailored to arm critical commands and to provide interlocks for configuration control. In the interest of reliability, these are held to a minimum.

Command Detection. The performance of a digital data channel is characterized by the bit error rate (BER) of the demodulated data. The BER measured as a probability of data error is determined by the S/N ratio at the input of a receiver.

The transmission of information in a PCM/FSK/AK/FM modulation system is contained in the carrier frequency deviation from a nominal center frequency. As in other forms of detection the recovery of the baseband information is achieved either by coherent detection or non-coherent detection. The improvement in efficiency of coherent detection as compared to noncoherent detection results in only a +1db improvement in S/N for equivalent bit error rates. Detection methods used are generally non-coherent detection.

In the simple case of a detector which detects a serial data stream, determining the presence of an envelope detected binary signal involves setting a threshold level at the detector output. When the threshold is exceeded it is assumed that a signal is present. When the threshold is not exceeded it is assumed that a signal is not present. There are two conditions which give false outputs, namely, the probability that noise in the absence of a signal exceeds the threshold and that additive noise when a signal is present results in the composite being more negative in value then the threshold setting. Both of these conditions will result in an error, i.e. in the first case (probability of false alarm) a zero will be detected as a ONE and in the second case (probability of false dismissal) a ONE will be detected as a ZERO. The probabilities of false alarm and false dismissal are determined from the noise density distribution known as the Rayleigh Distribution, which is the output of a diode when the input is corrupted by Gaussian noise. This is given by

$$P(R) = \frac{R}{\sigma^2} \exp\left[\frac{-R^2}{2\sigma^2}\right] \quad \text{for } R \geq 0$$

Figure 3 shows the function P(R). When the circular normal distribution has its center at a distance S from the origin, the distance R to the origin is distributed according to

$$P(R)\ dR = \frac{R}{\sigma^2}\left[e^{-\left[\frac{R^2 + S^2}{2\sigma^2}\right]} \, Io\left(\frac{Rs}{\sigma^2}\right)\right] dR$$

where Io = Bessel function of zero order with imaginary argument. This is the distribution of the envelope of a sine wave plus some Gaussian noise. Figure 4 shows the probability density of a sine wave with additive Gaussian noise.

The three parameters of interest are: probability of detection, P_d, probability of false alarm, P_{fa}, and probability of false dismissal, P_{fd}. These probabilities are shown in Figure 4. The probability of false dismissal is equal to 1-P where P_d is the probability of detection. Clearly a high order of P_d obtained with a low threshold level would produce a high P_{fa} (probability of false alarm). It becomes apparent that an optimum threshold value is one that provides for a P_{fa} equal to P_{fd} S. O. Rice derived expressions for relating P_d, threshold level, and P_{fa}. These values are given by:

$$\beta = \sqrt{-2 \operatorname{Ln} P_{fa}} \quad \text{and}$$

$$P_d = \int_\beta^\infty V \left[e^{-\left[\frac{V^2}{2} + \frac{S}{N}\right]} I_o\left(V \sqrt{2 \frac{S}{N}}\right)\right] dV$$

where β is the threshold level and V is the envelope of the signal plus noise current normalized by RMS noise current. S/N is the prededected S/N power ratio.

Now consider two channels of FSK in which the MARK or ONE channel is filtered and envelope detected and the SPACE or ZERO channel is filtered and envelope detected. The outputs of the two envelope detectors are differentially compared and a decision is made as to which output is the greater. The block diagram is shown in Figure 5. The probability of transmitting SPACE and receiving MARK is the same as the probability of transmitting MARK and receiving SPACE. The BER is therefore the probability that the average false alarm rate during the bit period from the no-signal channel exceeds the integrated carrier level from the signal channel. It is assumed that the two channels are perfectly matched and that the bit detector output is matched (i.e. $B_o\tau = 0.5$ where B_o is the output filter and τ is the bit period). The BER becomes

$$\tfrac{1}{2} e^{\left[\frac{-KA^2}{2\sigma^2}\right]}$$

where K is the threshold factor and KA = β. For the two channel case K is 1. In terms of the output E_b/N_o,

$$\text{BER} = \tfrac{1}{2} e^{\left[\frac{-E_b}{2N_o}\right]}$$

The BER performance is plotted in Figure 6.

The FSK demodulator as shown in Figure 5 contains SPACE and MARK filters preceded by an IF filter. The S/N at (e) Figure 5 is

$$(0.5)\,(0.84)\,\left(\frac{C}{N}\right) \frac{Bt}{2Bo}$$

for a matched baseband filter. When the baseband filter is a practical two-pole filter

$$\frac{S}{N} \text{ at } (e) = (0.9)\ (0.5)\ (0.84)\ \left(\frac{C}{N}\right)\ \frac{Bt}{2Bo}$$

$$\frac{C}{N_o} = [\ 2.65\ ]\,[E_b/N_o]\,[2Bo]$$

$$= [4.2 + E_b/N_o + 10\ \mathrm{Log}_{10}\ \text{BIT RATE}]\ \text{db}$$

For a BER of 10^{-5}

$$\frac{C}{N_o} = [17.5 + 10\ \log\ \text{bit rate}]\ \text{db}$$

The S/N at the receiver input has been evaluated. With reference to Figure 7 the system noise temperature (T_s) is

$$T_s = T_t + \frac{T_a}{L_a} + T_o\ [1 - \frac{1}{La}\ ] + T_o\ [\ L_t - 1] + T_o\ L_t\ \ [F_r - 1\ ]$$

This reduces to $T_s = 29OL_t\ F_r$ when $T_a = T_o$ 290°K and $T_t = 0$°K. L_t is typically -0.5db and F = 7 db.

The total system noise temperature is 319° + 150° = 1469° equivalent to 7.9 db.

A C/N_o of 37.5db at the input to the receiver is required for a BER of 10^{-5} at 100 bps.

For a receiver antenna gain of -7db the transmitted EIRP is 38.7dbW.

Reduction in EIRP is difficult to obtain by improving receiver noise temperature and G/T, due to the requirement for an isotropic antenna. Error correction coding may be employed for weak satellite relay links. A Hamming 15, 11 block code provides a 1.5db gain improvement at 10^{-5} BER. A convolutional code (constraint length 7) provides a 6.4db gain improvement at 10^{-5} BER.

The Command Processor. A simplified concept of a reliable command processor would picture a unit consisting primarily of an address detector, an acquisition register, a decode matrix, a power controller, and an output interface to using subsystems. In operation, an enable signal from the bit detector applies power to the processor logic. The processor logic verifies the address, loads the command message into the acquisition register, and generates a signal enabling power to the output interface. On receipt of the execute signal, the processor logic drives the output interface to provide pulse outputs and relay closures.

The principal requirement of the command processor is to minimize false outputs. Techniques to accomplish this encompass using good logic design practice, such as synchronous operation to avoid front and back porch signal transients and outputting large amplitude pulses to the using subsystem so that pulse receiver thresholds can be set well above noise levels. Spurious outputs during power-on or power-off transitions, such as eclipse mode in orbit, are prevented by having power applied to output interface circuits only when commands are processed.

While output signals are in general discrete commands, that is, a command message results in a single pulse output or a single relay closure, the use of proportional commands is not uncommon. Examples of this are digital words used for antenna positioning and for control of thruster firing. Implementation of the command processor can provide for transfer of the proportional work received as part of the command message to the using subsystem or for reduction of the word to a series of pulse outputs. The choice is one of spacecraft system design.

Achievement of Low Power. Power switching upon receipt of a valid command message provides a method of reducing power consumption. In the command unit, prior to the receipt of a command, only the bit detector and the verification logic of the processor have constant power. This standby mode typically requires four watts. On receipt of a command transmission, a signal from the bit detector enables the rest of the unit with an increase in power of about two watts. This operating mode of six watts continues as long as command transmission is present, reaching a maximum with command execution which may add a momentary four watts, as pulses or relay closures are distributed to the using subsystem. In normal spacecraft operation, the standby mode predominates, saving two watts over a continuously operating system in this example. When a decrypter is used in the spacecraft, additional and significantly greater savings can be realized by having the decrypter under similar control.

Considerations for a Decrypter. The location of a decrypter in a spacecraft is shown in Figure 8. As discussed earlier, use of the decrypter will dictate a vector execute system and impost a greater urgency to use power switching. An additional problem that presents itself is the reliability loss implied by the inclusion of the decrypter, which leads to developing decrypter by-pass strategies. By-pass is indicated by the dotted line in Figure 8. A non-exhaustive list of candidate solutions is:

1. Use a redundant decrypter to process a one-time command to bypass.
2. Use an on-board timer that will switch to by-pass if not periodically reset by command.
3. Use an on-board fault monitor that will switch to by-pass.

Consideration of the above will soon lead to the conclusion that there is no strategy without some unacceptable feature. Use of a redundant decrypter implies weight growth that is not likely acceptable on present fully loaded satellites. Reducing the decrypter to a single command decoder implies giving up command system security. Use of an on-board timer poses the difficult problem of time-out period selection. If the decrypter fails just after reset, command access is denied for the length of the timer. If the reset command is required often, ground station discipline may thwart the implementation. An on-board fault monitor requires some unambiguous detection of a non-working decrypter to avoid switching a good decrypter off-line.

As the above discussion implies, widespread use of decrypters awaits the development of an extremely reliable unit.

Considerations for Expendables. Expendable fuel on the satellite is that required to fire the apogee boost motor and control the thrusters. Firing of the boost motor is an irrevocable one time event and firing of thrusters consumes irreplaceable fuel. In order to protect against inadvertent ground command of those functions, an arming sequence may be implemented in the command processor and an additional command required from the ground station. In order to protect against unwanted pulse outputs from the command processor during periods when an electromagnetic pulse (emp) may occur, circuit design to negate the effects of circuit saturation are required. One way to accomplish this is to control the power applied to the pulse output circuits with a series-shunt transistor switch arrangement. In normal operation, the series switch closes to carry power to the output circuits. This is followed by opening of the series switch and closing of the shunt switch to discharge the output bus. With an emp disturbance both switches saturate to prevent a sufficient amplitude pulse from developing.

The Bus Supply. Like most spacecraft equipment, command units operate from dc/dc converters. The dc/dc converter with fold-back current limiting provides for failure isolation of the satellite power bus. Since the command unit must be on-line at standby at all times, and the vehicle bus may be low when the satellite comes out of eclipse, the converter is required to operate over a relatively wide voltage range. Typical bus parameters might require maintaining secondary converter voltages to the command unit with the primary bus in the range of 20 to 32 volts, with conducted interference of 0.5 volts peak-to-peak to 150 KHz, and in the presence of bus transients of ± 2 volts. Noise fed back on the bus due to converter operation would be held to less than 150 milliamps peak-to-peak to 150 KHz.

Remote Command Units. As satellites become larger and requirements for commands increase, the use of a central unit to process commands and distribute pulse and relay outputs appears cumbersome. Parallel interfacing with all using subsystems results in a harness complexity and weight that draws attention for potential weight saving. An alternative to the centralized implementation is a central command processor and remotely located command distributors with a serial data exchange between the central and remotes. This arrangement seeks judicial placement of the remotes in the satellite so as to minimize total harness weight and complexity. The arrangement is indicated by Figure 9. Variations of this arrangement would package remotes within chassis they service to further save weight.

The benefits of this approach are clearly visible if one pictures a very large vehicle. In reality, with the present size and complexity of the weather and communication satellites considered here, use of the decentralized system does not offer any clearly visible weight savings and does introduce additional complexity into test of the various satellite subsystems. The problem with the decentralization concept is that in a general discussion it is tacitly assumed that there is a central user of the commands in each subsystem. Examination of say the communication subsystem could reveal a number of individual receivers, rf switches, traveling wave tube amplifiers, and transmitters each requiring commands. In these relatively small spacecrafts, the additional hardware required to realize the remote and necessary harnessing in its dedicated subsystem does not warrant the additional complexity and often does not return the expected weight savings.

Redundancy and Cross-Strapping. The extent to which channelization, redundancy, and cross-strapping are implemented in a command system determines its reliability. At one end of the scale lies channelization, where system components such as the antenna, receiver, bit detector, and command processor are implemented once and a failure in one loses the system capability. Protection against this loss leads to redundancy, the providing of a second identically channelized system on stand-by. A complication here is that failure of the primary system, since it is the command system, may make it impossible to command the stand-by system into operation. As a result, redundant command systems are generally cross-strapped so that working components in the two channels can be interfaced to provide processing paths in addition to the two channelized ones.

A closer look at cross-strapping reveals that it can be implemented between system components or carried down to the circuit level. From a reliability viewpoint, the point of no return is where the reliability of an intended cross-strap gives no improvement over a baseline configuration.

A list of cross-strap techniques that could be used between system components include using different frequencies for receiver selection, different tone frequencies for bit detector selection, and digital addresses for command processor selection. One technique used in the past was to include an autonomous on-board timer to periodically cycle standby redundant units into operation. Circuit design techniques would focus on providing fail-safe interfacing.

An interesting cross-strapping technique uses an active sampler to cross-strap two receivers to two bit detectors. In essence, the bit detectors are connected by solid state switches that alternately sample the receivers. An important consideration in this technique is that when the bit detectors lock to the active receiver, having determined by a recognition criteria that a command baseband output is present, the off switches present a high impedance between that receiver and the bit detectors and provide for attenuating noise that might be present.

A Flight System. The command reception path of a recently launched communication satellite is shown in Figure 10. By comparison with Figure 1, the simplified system consisting of an antenna, bit detector, and command processor, additional components can be identified. The diplexer provides for sharing of the antenna with other satellite functions, specifically down link telemetry and ranging. The hybrid provides for frequency selection of the redundant receivers. The bit detectors are redundant and cross-strapped to the receivers by the active sampler discussed earlier. Redundant decrypters are included as well as redundant command processors. The combiner shown contains the output pulse drivers and relay contacts, pictured earlier as part of the command processor.

In operation, each of the bit detectors sequentially samples the outputs of the receivers. Upon recognition of valid uplink command modulation, each bit detector stops on the active receiver and enables power to its associated command decrypter. Since the decrypters have different addresses, only one will accept and process the incoming message. A preamble output from the processing decrypter enables power to be applied to its associated command processor and combiner. A vector execute system is used, with discrete commands requiring a two command transmission, store-execute. The command process is monitored via telemetry so that erroneous commands can be erased by re-transmission before an execute is sent. Error protection for the instruction vectors is provided by separating the vectors by a suitable hamming distance. To eliminate the need for reacquisition of the system due to momentary signal drop out, a turn-off delay of about one second is built into the tracking receiver and the active sampler. As can be seen, the system includes some channelization, redundancy, and cross-strapping. Figure 11 displays the four equipment configuration modes possible with this arrangement.

The reliability of this system has been specified to a probability of survival of 0.9049 for seven years on station and 0.9997 for the 55 hours required for launch and transfer orbit. The bit error performance measured at the bit detector has been found to be typically 10^{-6} at E_b/N_o of 18db. This is about 2.5db worse than theoretical for this system using a two-pole Butterworth filter.

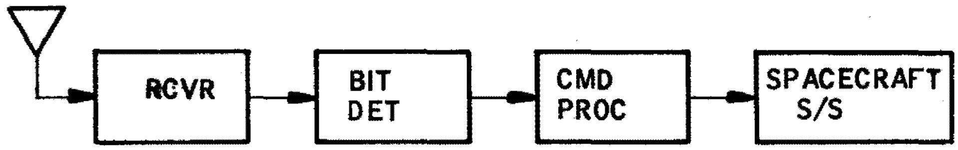

FIGURE 1. SIMPLIFIED COMMAND SYSTEM

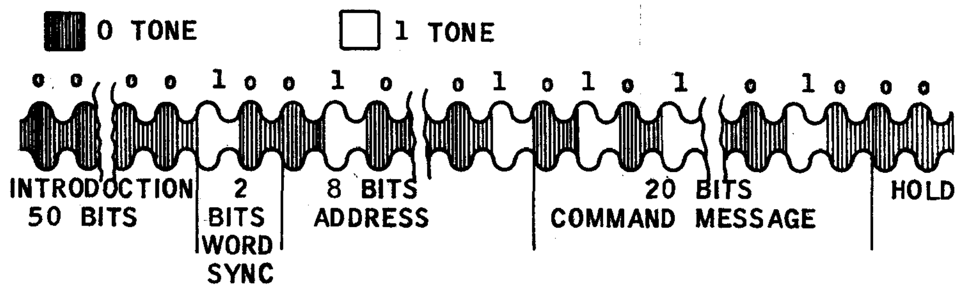

FIGURE 2. COMMAND SIGNAL STRUCTURE

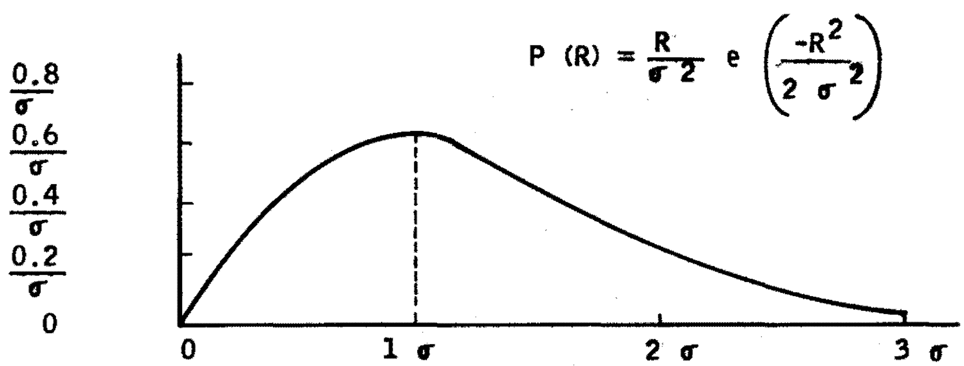

FIGURE 3. RAYLEIGH DISTRIBUTION

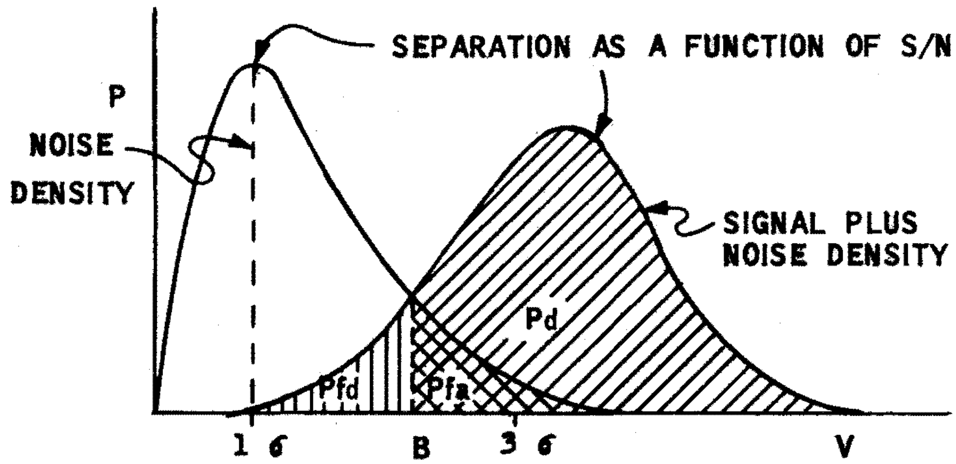

FIGURE 4. PROBABILITY DENSITY SIGNAL PLUS NOISE

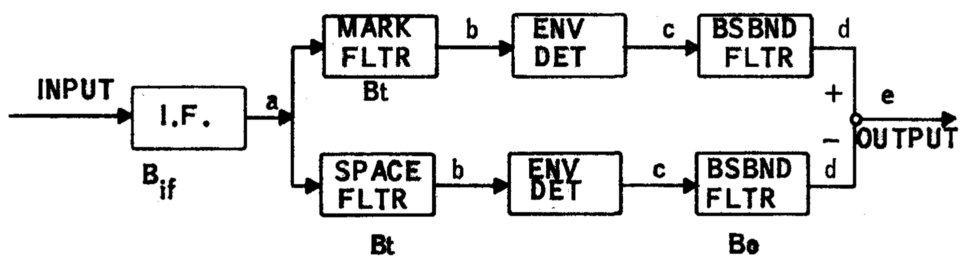

FIGURE 5. F.S.K. DEMODULATION

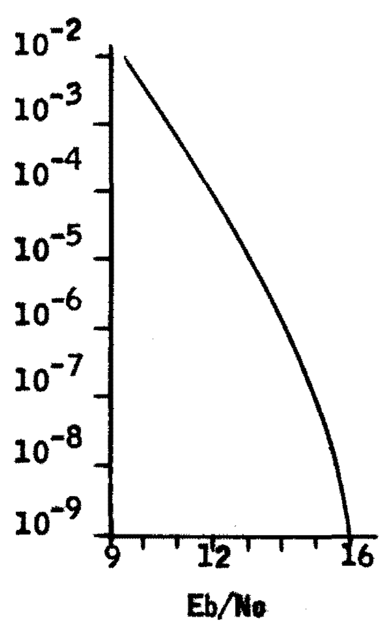

FIGURE 6. B.E.R. NONCONERENT F.S.K.

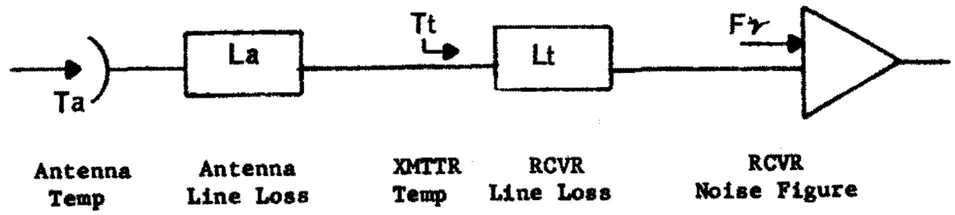

FIGURE 7. SYSTEM NOISE TEMPERATURE

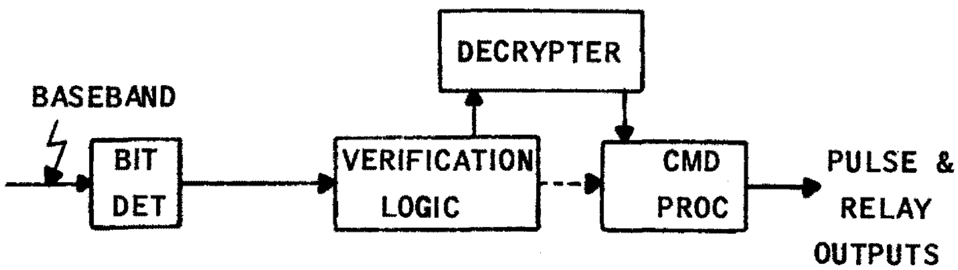

FIGURE 8. DECRYPTER PLACEMENT

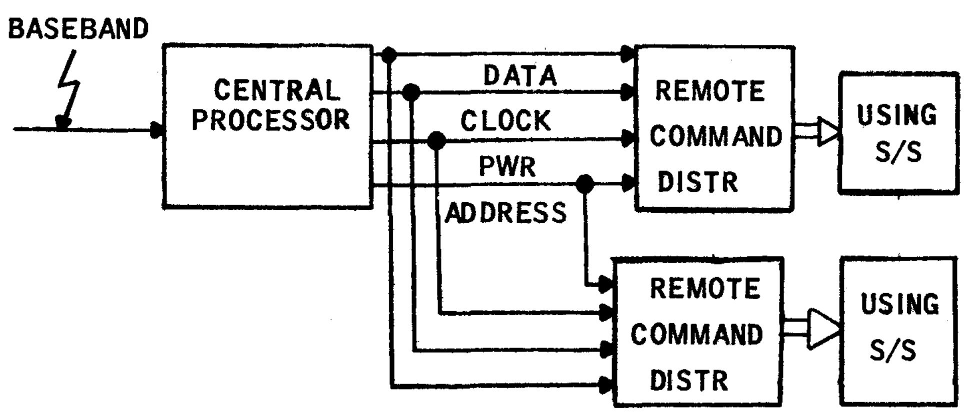

FIGURE 9. DECENTRALIZED COMMAND SYSTEM

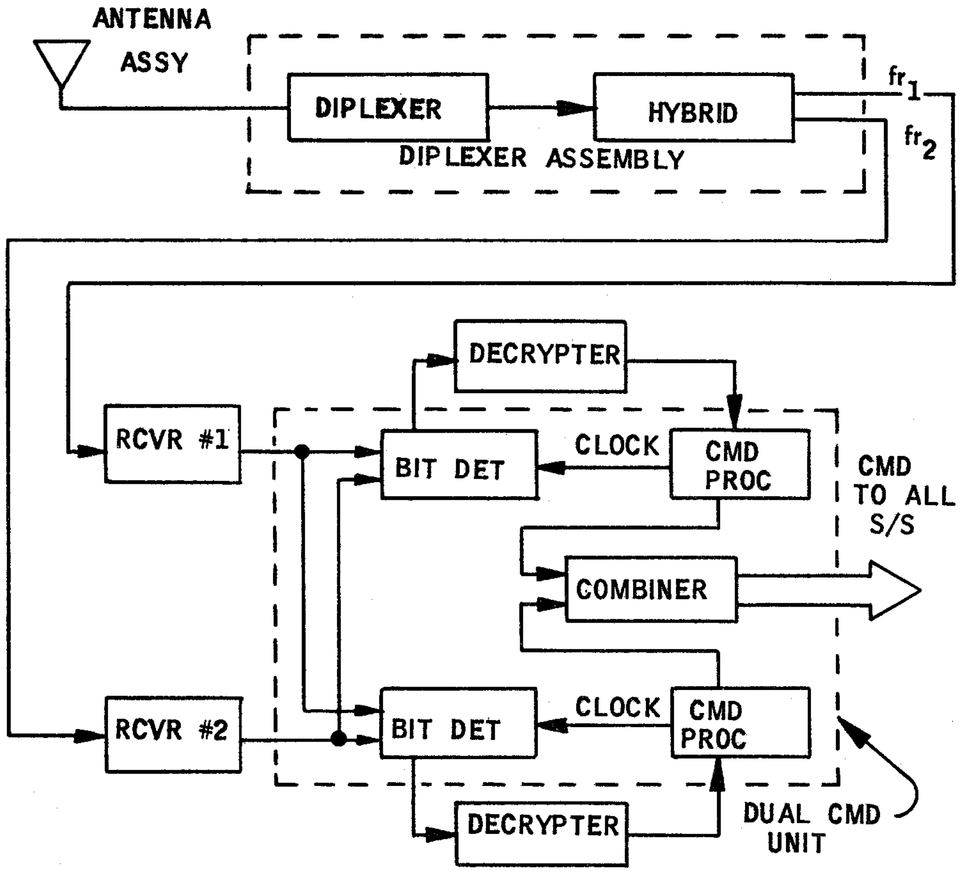

FIGURE 10. COMMAND RECEPTION FUNCTIONAL BLOCK DIAGRAM

MODE	EQUIPMENT CONFIGURATION					
	RECEIVER (SELECTED BY UPLINK FREQ.)		COMMAND UNIT SELECTED BY BIT DET.)		DECRYPTER (SELECTED BY I.D.)	
	NO. 1	NO. 2	NO. 1	NO. 2	NO. 1	NO. 2
C1	X		X		X	
C2	X			X		X
C3		X	X		X	
C4		X		X		X

FIGURE 11. COMMAND RECEPTION OPERATIONAL MODES