SHUTTLE PAYLOAD S-BAND COMMUNICATIONS SYSTEM

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ABSTRACT

The Shuttle payload S-band communications system design, operational capabilities, and performance are described in detail in this paper. System design requirements, overall system configuration and operation, and laboratory/flight test results are presented.

Payload communications requirements development is discussed in terms of evolvement of requirements as well as the resulting technical challenges encountered in meeting the initial requirements. Initial design approaches are described along with cost-saving initiatives that subsequently had to be made. The resulting system implementation that was finally adopted is presented along with a functional description of the system operation. A description of system test results, problems encountered, how the problems were solved, and the system flight experience to date is presented. Finally, a summary of the advancements made and the lessons learned is discussed.

INTRODUCTION

In the Shuttle payload S-band communications system, one Earth-orbiting satellite monitors and controls various functions of another Earth-orbiting satellite. Previously, this capability resided only in large Earth stations specifically implemented to monitor and control various manned and unmanned satellites.

Since a wide variety of satellites will be deployed and/or retrieved by the Shuttle, a major challenge was to engineer a communications system that could (1) generate commands having payload-compatible formats, data rates, and carrier frequencies and (2) monitor telemetry signals having various standard formats, data rates, subcarrier frequencies, and carrier frequencies. In addition, it was determined that to keep the implementation complexity within the realm of possibility, the system should provide the capability to relay nonstandard telemetry (via the Orbiter K_u-band communications system) to the ground without onboard subcarrier demodulation and bit synchronization. Similarly, it was decided that the system should be capable of accommodating nonstandard commands generated onboard the Orbiter by payload-unique processors.

This paper describes the early activities that resulted in an initial definition of the detailed functional and performance requirements of the Shuttle payload S-band communications system. It also describes the design concept developed to satisfy the initial requirements and discusses a reduced set of requirements which was later developed to simplify the implementation. The simplified implementation approach is also described in some detail.

The results of system-level testing in the Electronic Systems Test Laboratory (ESTL) are summarized, with emphasis on the problem areas encountered and on the solutions. The flight experience on the S-band payload communications system (PCM) is also discussed. Finally, the advancements made in the S-band payload communications system and some of the lessons learned by the NASA and contractor engineers directly involved in its development are briefly addressed.

INITIAL PAYLOAD COMMUNICATIONS REQUIREMENTS

The Shuttle payload S-band communications system requirements evolved over a period of several years during the mid 1970's through a series of meetings with various government and commercial organizations engaged in developing free-flying satellites for the 1980's. A set of general requirements directed by Level I program operational requirements concerning payload accommodations in the areas of safety, on-orbit payload deployment, checkout and retrieval mandated implementation of a short range payload radiofrequency (RF) communications system on the Orbiter. In the summer of 1974, an extensive meeting was held at the NASA Johnson Space Center (JSC) with representatives from many prospective Shuttle payload organizations. They were invited to make suggestions on how the Shuttle could best service their specific payloads (satellites). Their main points of interest were in terms of data and command rates, formats, modulation schemes, and carrier and subcarrier frequencies. The inputs received were quite varied. It soon became apparent that the Shuttle payload communications system would have to be designed as an orbital S-band ground station (indeed, three ground stations) that would be able to support Ground Space Flight Tracking and Data Network (GSTDN), Deep Space Network (DSN), and Tracking and Data Relay Satellite System (TDRSS) compatible payloads (satellites). In

TABLE 1.- SHUTTLE PAYLOAD S-BAND COMMUNICATIONS SYSTEM
(INITIAL REQUIREMENTS)

Requirement	Return link (telemetry)	Forward link (commands)
Carrier modulation	PM	PM
Modulation index	1.0 rad	1.0 rad
Data rates	16, 8, 4, 2, 1 kbps 256, 128, 64, 32, 16, 8, 4, 2, 1 bps	2000, 1000, 500, 250, 125, $\frac{125}{2}$, $\frac{125}{4}$, $\frac{125}{8}$, $\frac{125}{16}$, $\frac{125}{32}$ $\frac{125}{64}$, $\frac{125}{128}$ bps
Subcarriers	1.7 and 1.024 MHz 512, 256, 128, 64, 32, 16, 8, 4, 2, 1 kHz	16 kHz
Subcarrier modulation	All subcarriers PSK except 1.7 MHz - IRIG FM/FM	PSK
PCM formats	Biphase L, M, S NRZ L, M, S	Biphase L, M, S NRZ L, M, S
Special processing	Spread spectrum demodulation[a]	Spread spectrum demodulation[a]

[a] Required for TDRS-compatible payloads.

TABLE 2.- SHUTTLE PAYLOAD S-BAND COMMUNICATION SYSTEM RF CHANNELIZATION
INITIAL REQUIREMENTS

Requirement	Frequency range, MHz	No. of channels	Channel spacing, kHz
GSTDN/TDRS compatible payloads			
Orbiter transmit	2025.833 to 2118.7	808	115
Orbiter receive	2200 to 2300.875	808	125
DSN compatible payloads			
Orbiter transmit	2110.243 to 2119.792	29	241.049
Orbiter receive	2290.185 to 2299.814	27	370.37

addition, because the Shuttle would act like a ground station as far as its payloads were concerned and would simultaneously communicate with some of the same ground station elements that employed the same signal characteristics as the Shuttle, a technique was needed to minimize the expected interference between S-band links.

The initial system requirements and modulation characteristics from this meeting and from subsequent interaction between JSC and the payload community resulted in adoption of the characteristics shown in table 1 and the RF channelization shown in table 2 to support GSTDN, TDRSS, and DSN compatible satellites. These initial requirements approved by the Shuttle Program were intended to accommodate virtually every conceivable payload RF system implementation that might be fabricated to fly against any one of the three existing ground networks (TDRSS, GSTDN, and DSN).

The RF communication accommodation for deployable payloads was again driven by the top-level operational requirement to provide onboard, real-time, command control, and monitoring of payloads to support deployment, checkout, and retrieval activities.

INITIAL DESIGN APPROACH

The design concept initially conceived to provide the system capabilities outlined above centered around fabrication of two line replaceable units (LRU's) and one flush-mounted S-band antenna located on top of the Orbiter just forward of the payload bay opening. The two LRU's consisted of a highly flexible multichannel S-band transponder called the payload interrogator (PI) and a many-faceted, multifunction, extremely complex payload signal processor (PSP). Figure 1 illustrates the functional configuration of the payload S-band communications system as it interfaces with a typical deployed payload.

The initial system requirements resulted in a number of stringent system design drivers for the two LRU's. Specifically, the payload interrogator would be required to (1) generate more than 800 pairs of transmit and receive frequencies, (2) provide multiple modulation/demodulation schemes, and (3) perform spectrum spreading and despreading for TDRSS compatible payloads. The payload signal processor would have to (1) generate and modulate many command subcarrier frequencies, (2) detect and demodulate many telemetry subcarrier frequencies, (3) generate and process six pulse-code modulated (PCM) formats, (4) bit synchronize on over 100 possible bit rates, and (5) perform frame synchronization for many formats.

To perform all these functions on the ground would require enormous complexity (the equivalent of three ground stations in one); to try to perform all of these functions in space was quickly recognized as too costly and impractical. Technically, the challenges could have been met, given an unlimited source of funding and sufficient time to develop and package the flight hardware. However, with the funding problems the Shuttle program was beginning to encounter at that time across the board, the need to greatly simplify the payload S-band communications system was recognized.

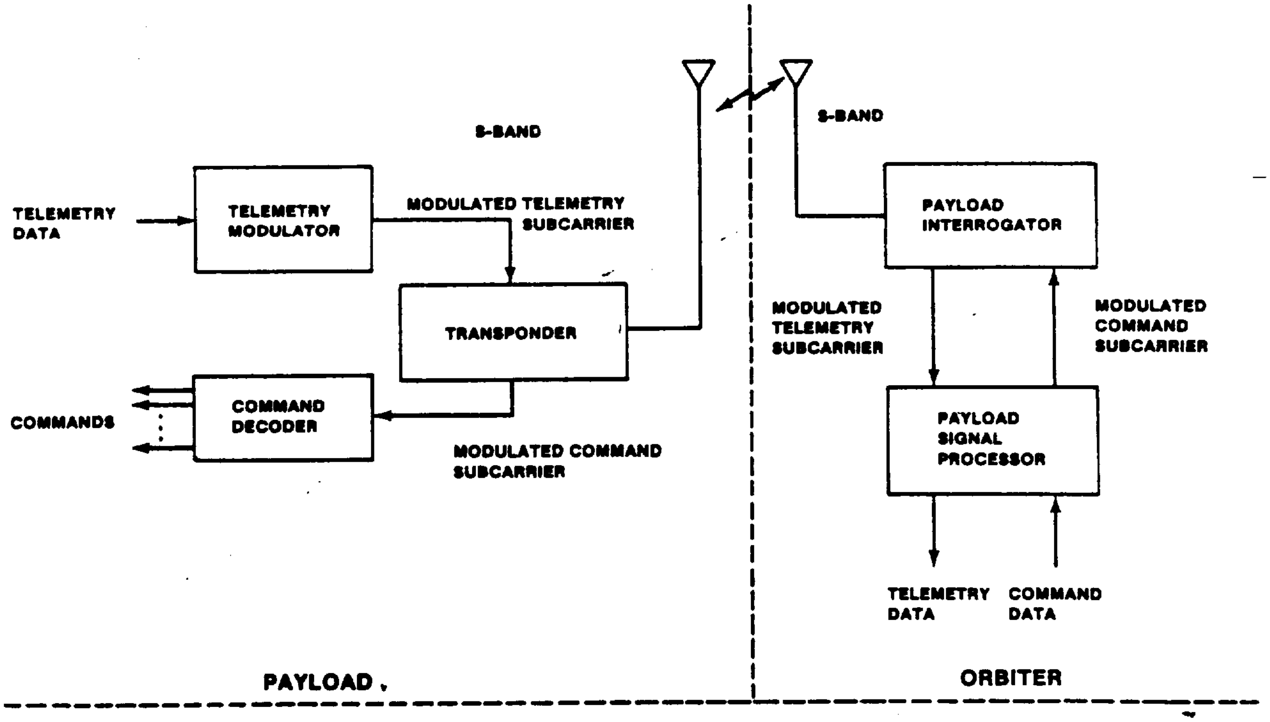

FIGURE 1.- ORBITER PAYLOAD S-BAND COMMUNICATIONS SYSTEM FUNCTIONAL CONFIGURATION (INITIAL).

The Shuttle program management then initiated a review of payload RF communications requirements along with technical factfinding of various system simplification options. This series of reviews and technical assessments resulted in the program management decision to make the following changes.

1. Delete the forward and return link spread spectrum capability.

2. Provide normal baseband signal processing functions for only a limited number of modulation schemes, subcarriers, bit rates, PCM formats, etc. (i.e., a set of "standard" signals).

3. Implement a transparent throughput "bent-pipe" capability to relay "nonstandard" payload signals to the ground via the Orbiter K_u-band link for ground monitoring.

It was decided that these changes would result in greatly simplified Orbiter hardware and significant reductions in cost, weight, and development risk to the Orbiter. The total savings to the program as a result of these changes was estimated at the time to be approximately $20 million.

Tables 3 and 4 show the revised set of payload S-band communications system characteristics based on the updated system requirements and adopted standard versus nonstandard payload concept. The RF channelization reflected in table 3 was unchanged from the initial concept. The decision was made to pursue implementation of the total GSTDN/TDRSS/DSN complement of operating frequencies using a frequency synthesizer approach. Table 4 shows the revised command and telemetry signal processing characteristics for the standard payload.

TABLE 3.- SHUTTLE PAYLOAD S-BAND COMMUNICATION SYSTEM RF CHANNELIZATION

Requirement	Frequency, MHz	No. of channels	Channel spacing, kHz
GSTDN/TDRS			
Transmit	2025.833 to 2117.916	801	115
Receive	2200 to 2300	801	125
DSN			
Transmit	2110.243 to 2119.792	29	241.049
Receive	2290.185 to 2299.814	27	370.37

TABLE 4.- SHUTTLE PAYLOAD S-BAND COMMUNICATIONS SYSTEM STANDARD COMMAND AND TELEMETRY REQUIREMENTS

Requirement	Return link (telemetry)	Forward link (commands)
Carrier modulation	PM	PM
Modulation index	1.0 rad	1.0 rad
Subcarrier frequency	1.024 MHz	16 kHz
Subcarrier modulation	PSK	PSK
Data rates	16, 8, 4, 2, 1 kbps	2000, 1000, 500, 250, 125, $\frac{125}{2}$, $\frac{125}{4}$, $\frac{125}{8}$, $\frac{125}{16}$ bps
PCM formats	NRZ L, M, S Biphase L, M, S	NRZ L, M, S

IMPLEMENTATION APPROACH SELECTED

The simplified Shuttle payload RF communications concept on which the final implementation approach was based called for a standard interface capability to provide normal baseband processing functions for a defined set of standard signals and nonstandard interface capability to provide a telemetry throughput to the ground via a transparent channel (bent pipe) or to the Orbiter aft flight deck payload station. Functionally, the nonstandard mode would be accomplished by having the payload interrogator strip out a baseband (or intermediate frequency (IF)) unprocessed version of the nonstandard signal and route it to the ground via the K_u-band TDRSS link, time shared with television (FM mode 2), or by routing the signal to a payload-supplied unique signal processor located in the aft flight deck payload station.

Simplification of the initial requirements and implementation concept did not change the basic LRU concept shown in figure 1; however, it did allow a great reduction of internal LRU complexity. The payload interrogator complexity was reduced by eliminating the spread spectrum capability. The PSP complexity was reduced by eliminating several modulation scheme, subcarrier, data rate, command rate, and PCM format options and the attached payload (hardline) telemetry capability. This capability already existed in the payload data interleaver (PDI) design.

Figure 2 shows the functional configuration of the final payload S-band communications system implementation, including the added interfaces with the K_u-band signal processor and the aft flight deck payload station. Figure 2 also shows LRU redundancy. Figure 3 illustrates how the final system configuration interfaces with the overall Orbiter avionics system. In figure 2, either nonstandard or standard telemetry formats can be sent directly to ground (unprocessed) via the K_u-band system in the bent-pipe mode. Nonstandard payload telemetry, which must be processed onboard for display, recording, or monitoring, is routed from the PI to the payload station distribution panel where it is sent to a payload-supplied unique signal processor. This same processor may also be used to generate nonstandard command formats and output them to the PI for transmission to the detached payload. Standard telemetry and command formats listed in table 4 are processed onboard by the PSP as a standard Shuttle service.

PAYLOAD INTERROGATOR

The PI provides the RF communication link between the Orbiter and detached payloads. For communications with the standard payloads, the PI operates in conjunction with the PSP.

During most nonstandard missions, the PI is interfaced with a Payload Station Distribution Panel (PSDP) unique signal processor. Nonstandard data received by the PI can also be routed to the K_u-

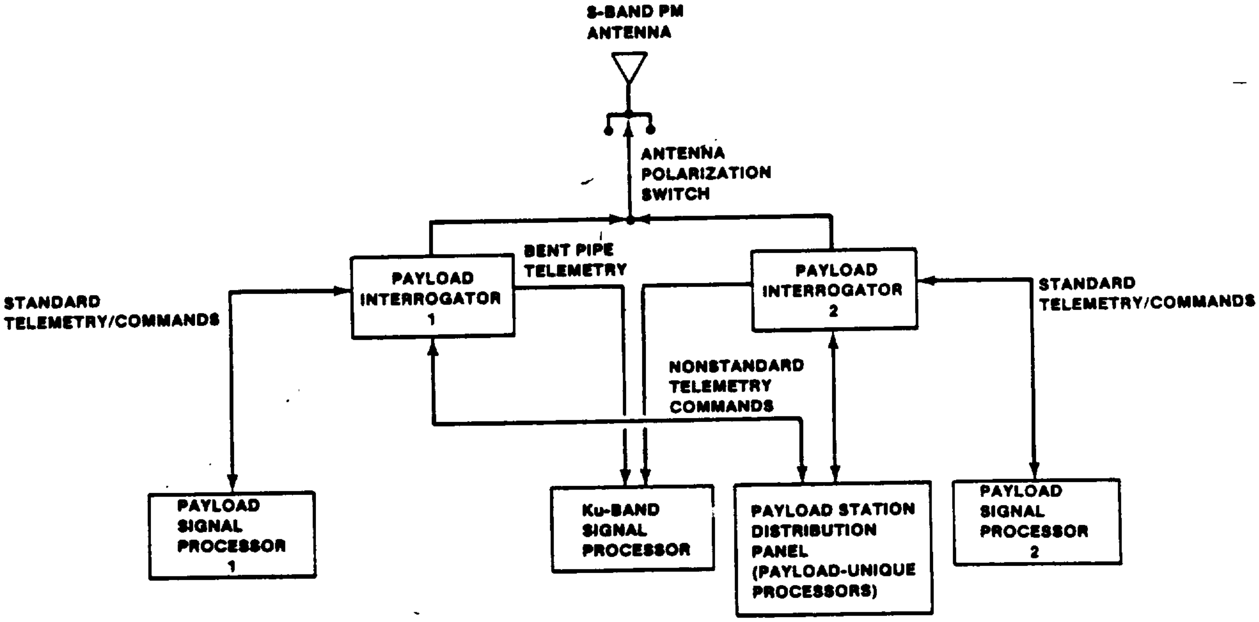

FIGURE 2.- ORBITER PAYLOAD S-BAND COMMUNICATIONS SYSTEM FUNCTIONAL CONFIGURATION (FINAL).

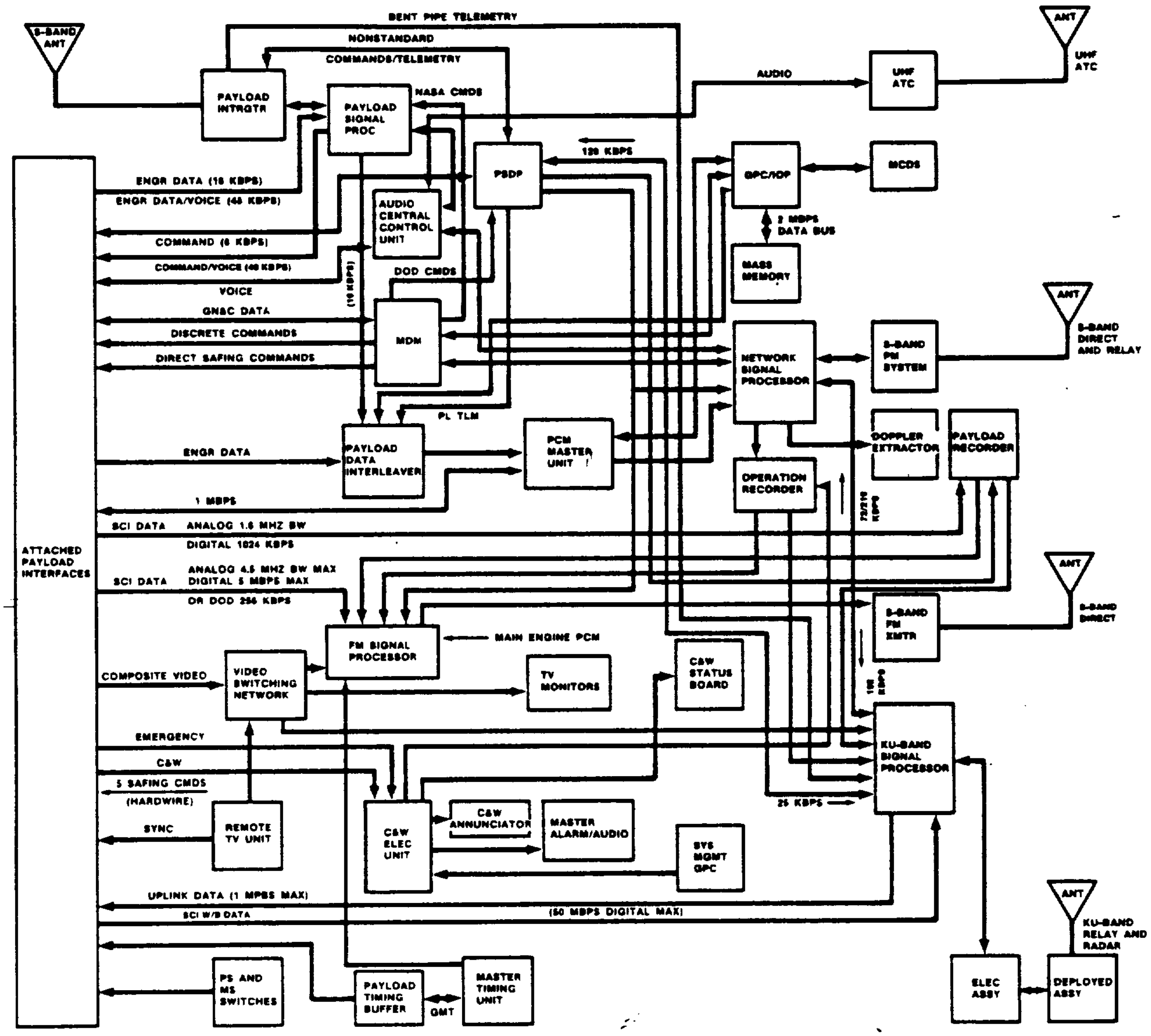

FIGURE 3.- SHUTTLE ORBITER AVIONICS SYSTEM.

band signal processor, where it is processed for transmission to the ground via the Shuttle K_U-band/TDRSS link (bent pipe).

Simultaneous RF transmission and reception is the primary mode of PI operation with both standard and nonstandard payloads. The Orbiter-to-payload link carries the commands, while the payload-to-Orbiter link communicates the telemetry data. In addition to this duplex operation, the PI provides for "transmit only" and "receive only" modes of communication with some payloads.

Figure 4 shows the functional block diagram for the PI. The antenna connects to an input/output RF port which is common to the receiver and the transmitter of the PI unit. A dual triplexer is used because of a requirement to operate the PI simultaneously with the Shuttle/ground S-band network transponder, which radiates and receives on the same frequency bands. The Shuttle S-band network transponder emits a signal at either 2217.5 or 2287.5 megahertz. Both frequencies fall directly into the PI receive band of 2200 to 2300 megahertz. Conversely, the payload transmitter, operating in the 2025- to 2120-megahertz band, can interfere with uplink signal reception by the S-band network transponder receiver. Therefore, by use of the triplexer and by simultaneously operating the PI and network transponder in the mutually exclusive subbands, the interference problem is effectively eliminated.

In addition to the problem of potential interference due to the mutual, simultaneous operation of the S-band payload and S-band network communications system, there is also the problem of an extremely large range of power levels that must be accommodated. When detached payloads are in the immediate vicinity of the Orbiter, excessive RF power levels may impinge on the interrogator antenna. Thus, the RF preamplifier of the receiver is protected by a combination of sensitivity control attenuators and a diode breakdown limiter. The output of the preamplifier is applied to the first mixer where it is converted to the first IF for amplification and level control. The first local oscillator frequency, f_{L01}, is tunable and its frequency corresponds with the desired PI receive channel frequency. Except for channel selection, however, f_{L01} is fixed. Consequently, any unspecified frequency difference between the received payload signal and f_{L01} will appear within the first IF amplifier and at the input to the second mixer.

The receiver frequency and phase tracking loop begins at the second mixer. As shown in figure 4, the output of the first IF amplifier is down-converted to the second IF as a result of mixing with a variable second LO frequency, f_{L02}. The portion of the second IF which involves only the carrier tracking function is narrowband, passing the received signal residual carrier component and excluding the bulk of the sideband frequencies. Demodulation to baseband of the second IF signal is accomplished by mixing with a reference frequency, f_R. The output of the tracking phase detector, after proper filtering, is applied to the control terminals of a voltage controlled oscillator (VCO) which provides the second local oscillator signal, thereby closing the tracking loop. Thus, when phase track is established, f_{L02} follows frequency changes of the received payload signal.

For the purpose of frequency acquisition, the f_{L02} may be swept over a ±50-kilohertz uncertainty region. Sweep is terminated when the output of the coherent amplitude detector (CAD) exceeds a present threshold, indicating that the carrier tracking loop has attained lock. The output of the CAD also provides the automatic gain control (AGC) to the first IF amplifier. To accommodate payload-to-Orbiter received signal level changes caused by range variation from a few feet to 10 nautical miles, 110 decibels of AGC is provided in the first intermediate frequency amplifier (IFA).

A wideband phase detector is used to demodulate the telemetry signals from the carrier. The output of this detector is filtered, envelope level controlled, and buffered for delivery to the PSP, PSDP, and K_u-band signal processor units.

The PI receiver frequency synthesizer provides the tunable first LO frequency and the corresponding exciter frequency to the transmitter synthesizer. It also delivers a reference signal to the transmitter phase modulator. Baseband standard or nonstandard command signals modulate the phase of this reference signal, which is in turn supplied to the transmitter synthesizer where it is upconverted to the transmit frequency and applied to the power amplifiers.

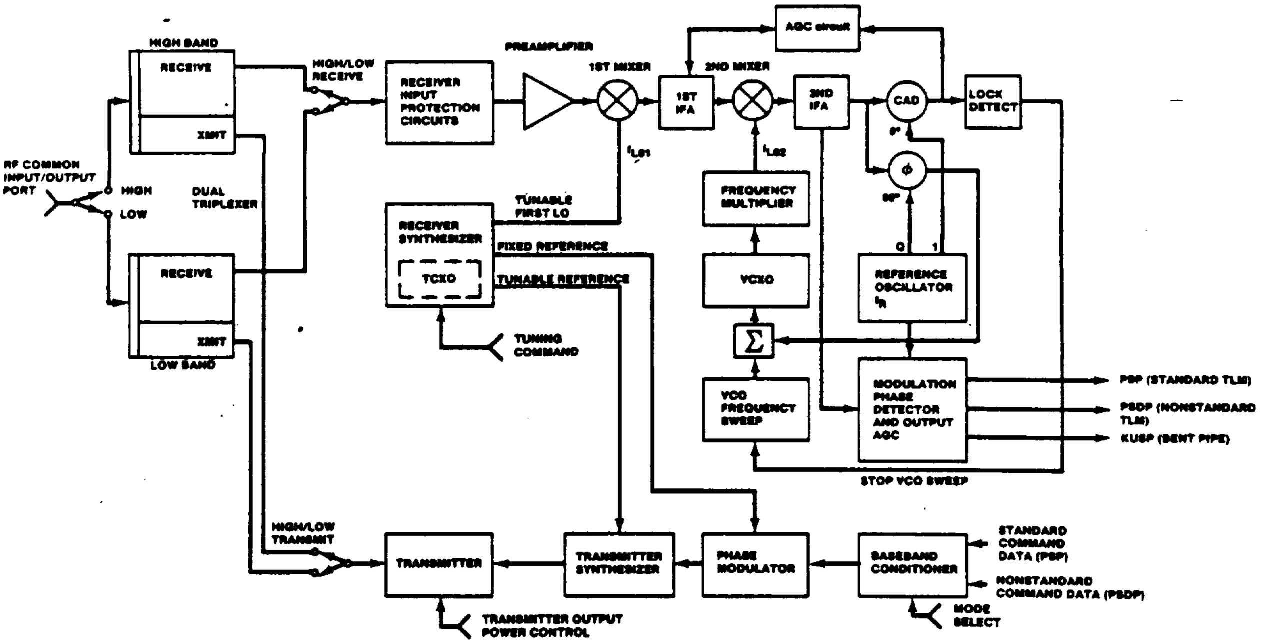

FIGURE 4.- PAYLOAD INTERROGATOR FUNCTIONAL BLOCK DIAGRAM.

Depending on the operating band selected, transmitter output is applied to either the high- or low-band triplexer. To compensate for varying distances to payloads, each transmitter has three selectable output power levels (5 to 10 dBm, 28 to 33 dBm, and 38 to 42 dBm).

PAYLOAD SIGNAL PROCESSOR

The payload signal processor (PSP) (1) modulates standard payload commands onto a 16-kilohertz sinusoidal subcarrier and delivers the resultant signal to the PI and to the attached payload umbilical, (2) demodulates the payload telemetry data from the 1.024-megahertz subcarrier signal provided by the PI, and (3) performs bit and frame synchronization of demodulated data and delivers these data and its clock to the payload data interleaver.

The PSP also transmits status messages to the Orbiter's general-purpose computers (GPC's). The status messages allow the GPC's to control and configure the PSP and validate command messages before transmission.

The functional block diagram for the PSP is shown in figure 5. The PSP configuration and payload command data are input to the PSP via a bidirectional serial interface. Transfer of data in either direction is initiated by discrete control signals. Data words 20 bits in length (16 information, 1 parity, 3 synchronization) are transferred across the bidirectional interface at a burst rate of 1 Mbps, and the serial words received by the PSP are applied to word validation logic which examines their structure. Failure of the incoming message to pass a validation test results in a request for a repeat of the message from the GPC.

Command data are further processed and validated as to content and the number of command words. The function of the command buffets is to perform data rate conversion from the Mbps bursts to one of the selected standard command rates. Command rate and format are specified through the configuration message control subunit.

From the message buffers, the command bits are fed via the idle pattern selector and generator to the subcarrier biphase modulator. The idle pattern, which often consists of alternating "ones" and "zeros," precedes the actual command word and is usually also transmitted in lieu of command messages. Subcarrier modulation is biphase non-return-to-zero (NRZ) only.

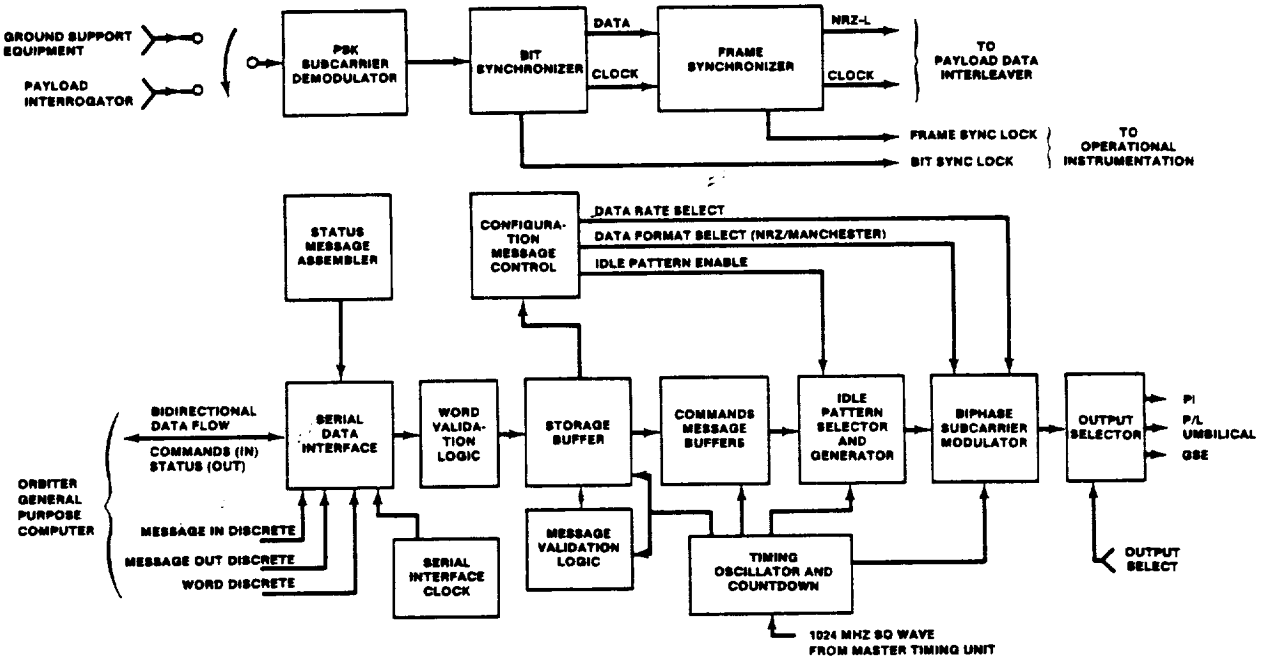

FIGURE 5.- NASA PAYLOAD SIGNAL PROCESSOR FUNCTIONAL BLOCK DIAGRAM.

The 1.024-megahertz telemetry subcarrier from the PI is applied to the PSK subcarrier demodulator. Since the subcarrier is biphase modulated, a Costas-type loop is used to lock onto and track the subcarrier. The resulting demodulated bit stream is input to the bit synchronizer subunit, where a DTTL bit synchronization loop provides timing to an integrate-and-dump matched filter which optimally detects and reclocks the telemetry data.

Detected telemetry bits, together with clock data, are input to the frame synchronizer where frame synchronization is obtained for any one of the four NASA standard synchronization words. The frame synchronizer also detects and corrects the data polarity ambiguity caused by the PSK demodulator Costas loop.

From the frame synchronizer, the telemetry data with corrected frame synchronization words and clock data are fed to the PDI. The telemetry detection units also supply appropriate lock signals to the Orbiter's operational instrumentation equipment, thus acting to indicate the presence of valid telemetry.

TEST RESULTS AND FLIGHT PERFORMANCE

RF compatibility tests were performed in the Electronic Systems Test Laboratory (ESTL) using the Orbiter's PI and PSP to communicate with several classes of payload communications systems. The payload communications systems tested were the Inertial Upper Stage (IUS); the Shuttle Pallet Satellite-01 (SPAS-01); the Tracking and Data Relay Satellite (TDRS) Telemetry, Tracking, and Command (TT&C) system; and the NASA near-Earth and TDRS user's transponders. Additionally, the PI and PSP were used during the fifth Shuttle flight (STS-5) to receive telemetry from the Satellite Business System (SBS) payload. During the sixth flight (STS-6), the PI was used to send commands to and receive telemetry from the IUS spacecraft. The PI and PSP were used for TDRS predeployment communication checkout.

PAYLOAD SIGNAL PROCESSOR PERFORMANCE

A major PSP problem, uncovered during the SPAS-01 transponder testing in the ESTL, was false locking of the bit synchronizer on NRZ-L telemetry. PSP false lock could occur by thresholding the PI receiver (similar to going through an antenna pattern null) and then increasing the total received power (TRP) to a value above data threshold.

The PSP bit synchronizer is implemented in a microprocessor. The modification to remedy the false lock problem consisted of changing the microprocessor software and making cuts and installing jumpers in the microprocessor printed circuit board.

The PSP was used for the first time during flight to process the telemetry from the SBS payload during STS-5. The aforementioned modifications had not been made to the STS-5 PSP to remedy the false lock problem for this mission; however, the conditions for false locking did not occur during SBS deployment and the PSP performance was excellent. The modifications to prevent false locking were made in the PSP used to support the predeployment checkout of TDRS-A during STS-6. Again, the PSP performance was excellent for both telemetry and command processing.

PAYLOAD INTERROGATOR PERFORMANCE

The ESTL RF compatibility tests using the PI with each major class of payload communication system showed that the PI was compatible with each and that all performance requirements were met. The most significant finding during the IUS and SPAS-01 tests was that simultaneous transmission of television via the FM transmitter on 2250.0 megahertz could interfere with the PI return link telemetry reception. This interference is most certain to occur (1) when the payload transmit frequency is within 15 megahertz of the FM transmitter frequency, (2) when the payload is greater than 1 kilometer from the Orbiter, and (3) when television video is being transmitted via the upper FM hemispherical antenna. The simultaneous occurrence of these conditions can be avoided operationally.

Excessive phase noise was detected on the ESTL prototype unit. After the unit was returned to the vendor for repair, a faulty capacitor was found and replaced. No further design deficiencies were uncovered during ESTL testing.

The PI was used for the first time during a mission to receive the return link telemetry signal from the SBS payload during STS-5. The PI performance was excellent. The PI was also used on STS-6 for transmitting commands and receiving telemetry in conjunction with the predeployment checkout and deployment of the IUS and TDRS-A spacecraft. Again, the PI performance was excellent.

CONCLUSIONS

Development of a spaceborne system to provide the capability for monitoring and controlling nearby satellites is a significant milestone. Expansion of this capability will most assuredly be required if a space station is to be developed. Such expansion will undoubtedly include a multi-access capability to allow simultaneous monitoring and control of multiple satellites as well as an extended range capability.

The merits of designing a multipurpose system such that a standard onboard processing capability is provided for most users while a "bent-pipe" relay capability is provided for the relatively few nonstandard users were found to be more than theoretical. Significant savings in cost, weight, and complexity were realized. These savings clearly demonstrate the necessity to "scrub" requirements and to explore alternate design approaches before implementing a complex system.

The necessity of performing end-to-end system performance testing for complex communications systems was (once again) demonstrated. Although the S-band payload system LRU's underwent extensive vendor-level testing (prototype, qualification, and acceptance testing) and a certain level of prime contractor integrated system testing, the major problems that occurred were not manifested until the system was thoroughly tested in ESTL. Uncovering these problems through ESTL testing (detailed end-to-end system compatibility testing) rather than during real-time mission operations allowed the opportunity to adequately analyze and resolve the system performance deficiencies early on instead of risking compromised mission success.

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