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ELECTRONICS SYSTEMS TEST LABORATORY TESTING OF SHUTTLE COMMUNICATIONS SYSTEMS

C. Jack Stoker and Linda K. Bromley
NASA Lyndon B. Johnson Space Center
Houston, Texas

ABSTRACT

Shuttle communications and tracking systems space-to-space and space-to-ground compatibility and performance evaluations are conducted in the NASA Johnson Space Center Electronics Systems Test Laboratory (ESTL). This evaluation is accomplished through systems verification/certification tests using Orbiter communications hardware in conjunction with other Shuttle communications and tracking external elements to evaluate end-to-end system compatibility and to verify/certify that overall system performance meets program requirements before manned flight usage. In this role, the ESTL serves as a multi-element major ground test facility. This paper provides a brief description of the ESTL capability and program concept. The system test philosophy for the complex communications channels is described in terms of the major phases. A summary of results of space-to-space and space-to-ground systems tests is presented. Several examples of the ESTL's unique capabilities to locate and help resolve potential problems are discussed in detail.

INTRODUCTION

The Electronic Systems Test Laboratory was established in 1964 as the only practical means of development, and subsequent certification by testing, of space/ground communications systems on an end-to-end basis. Space vehicle communications subsystems, unlike other subsystems, must interface not only with other subsystems on the space vehicle but also, by radiofrequency, with remotely located external equipment. These external interfaces include the Ground Space-Flight Tracking and Data Network (GSTDN), the Air Force Satellite Control Facility (AFSCF), the Tracking and Data Relay Satellite System (TDRSS), NASA and Department of Defense (DOD) detached payloads, and extravehicular communications systems. Descriptions of the Shuttle communications modes and systems configurations can be found in references 1 to 3.

Reliable communications between the Orbiter space vehicle and its external elements are mandatory for successful missions. The early manned-space-flight programs (Mercury and Gemini) used, primarily, off-the-shelf aircraft-type communications systems. These systems had been developed previously and a proven capability had been demonstrated, primarily by the military. These systems were accepted for space flight using ground support equipment to simulate the functions of the external communications equipment. The actual space vehicle and the external communications equipment were not interfaced until tests at the launch facility. As the communications systems became more complex, a new philosophy was needed. The advent of more complex high information rate communications systems, such as the Apollo unified S-band system and the Shuttle TDRSS space-to-space and space-to-ground multiple configurations, requires a more thorough and comprehensive program for compatibility and performance certification before the first use on manned missions. The ESTL was established as the most practical way to provide the unique capability to interface space vehicle communications equipment and its external counterparts in a laboratory environment. This capability is used to develop and verify that equipment is compatible and that the performance provided by these communication links meets program requirements.

The Space Shuttle communications system consists of major hardware elements that can be generally categorized as space elements and ground elements. Before release of hardware specifications, analytical models are developed to determine system feasibility and potential performance capabilities. As the analytical phase progresses, many problems/questions arise that are not analytically tractable but lend themselves to experimental evaluation. Thus, to supplement the analysis, early system-level tests are conducted using breadboard hardware. During hardware development (after contract award), the analysis and breadboard testing continue to be essential elements in resolving specification conflicts which arise as the hardware design matures. After design/development of the system hardware, system verification testing using prototype hardware is accomplished. These tests establish basic system compatibility and performance and provide a means to identify any modifications required if an incompatibility or performance deficiency exists. The final phase of hardware development includes system performance certification, which entails verification that the flight-configured systems are compatible and will meet mission performance requirements. If problems are encountered at this level of testing, either hardware modifications or mission constraints result. To avoid the serious consequences of performance certification problems, the Shuttle Program Office has established the Space Shuttle communications and tracking systems ground testing program at the NASA Johnson Space Center (JSC). This program provides three basic phases: (1) system design evaluation tests using breadboard hardware, (2) system verification/certification tests using prototype hardware (or flight-type hardware when differences exist between flight-type and prototype hardware), and (3) special tests involving operational configurations and/or concepts. The remainder of this paper describes, in more detail, the test philosophies, techniques, and results associated with each of these test phases.

ESTL TEST CONCEPT

The ESTL provides the unique capability to interface space vehicle communications equipment with its external counterparts in a laboratory environment under closely controlled conditions. Particular emphasis is placed on new, complex, and unproven system designs. Test conditions are closely controlled by any combination of such factors as the total received power levels and the presence or absence of static or dynamic Doppler, data encoding, spectrum spreading, bit jitter, and/or data asymmetry, etc. These factors can be varied individually to determine their effect on the system or set to their nominal mission values to determine overall expected end-to-end system performance. Use of the ESTL capabilities enables early verification of communications systems compatibility and performance.

The concept used in the implementation of testing in the ESTL is illustrated in figure 1 for certification test phases. Operational Shuttle Orbiter hardware electrically equivalent to flight hardware is obtained through the prime contractor and interconnected such that the resultant subsystem is equivalent to the Orbiter Communications and Tracking Subsystem. The hardware is then installed in one of four radiofrequency (RF) shielded enclosures in the ESTL. The ESTL Orbiter/spacecraft test area is shown in figure 2. The space vehicle communications subsystem is interconnected with the external elements (GSTDN, TDRSS, AFSCF, extravehicular systems, or payloads) through space loss simulators. The relay satellite, extravehicular systems, and payloads are also installed in shielded enclosures.

The space loss simulators provide precise control of the power levels for the K_u-band, S-band, and ultrahigh frequency (UHF) signals delivered to the receiving systems. The ESTL space loss simulator is shown in figure 3. For S- and K_u-band waveguide configurations, a dry air system is required to maintain constant waveguide characteristics and thus preserve the space loss simulator accuracy. The space loss simulator also provides the capability to induce dynamic or static Doppler onto the RF signal and its modulation. Patch panels enable routing of signals between any of the four shielded enclosures, the GSTDN ground station equipment, the AFSCF ground station equipment, and the TDRSS (space and ground segment) equipment.

The GSTDN equipment installed in the ESTL was obtained through the NASA Goddard Space Flight Center (GSFC) and is identical to the equipment located in NASA's worldwide network. Equipment from one of the AFSCF remote tracking sites was modified and provided by the Air Force to accommodate interface certification with the Shuttle Orbiter. The TDRSS ground station equipment (fig. 4) installed in the ESTL was procured from various vendors by part numbers and is identical to the S-band and K_u-band single access equipment in the ground station at White Sands, New Mexico. The TDRSS equipment located in the ESTL represents a functional simulation of the single access characteristics of the actual satellite. Specifications for the simulation system were developed in coordination with cognizant engineers at GSFC. A functional simulator of the TDRS (space and ground interface segments) is presently installed in the ESTL. TDRSS ground station hardware is updated as necessary to ensure that high-fidelity operational TDRSS configurations are maintained.

The test control center in the ESTL (fig. 5) serves as the central location for coordination of test activities. It also has the capability to generate test activities. Additionally, the generation and evaluation of audio and television video signals, measurement of bit error rates (to 150 Mbps), command evaluation, space loss simulator control, and remote control of GSTDN equipment are initiated from the test control center. The measurements and data comparisons performed in the test control center are recorded by keyboard entry into the real-time data analysis and prediction system.

To perform system-level tests, several types of measurement techniques must be employed. These techniques include the statistical measurement of bit error rate (BER) (probability), signal-to-noise ratios (SNR's), and voice quality (made in conjunction with the U.S. Army Test and Evaluation Command at Fort Huachuca, Arizona). Details of techniques to make these measurements can be found in reference 4. Several unique measurement techniques have been developed such as an automated system (Statistical Loop Analyzer, ref. 5) for measuring acquisition, tracking, and frequency stability performance characteristics. Evaluation of the performance of the Space Shuttle communications and tracking systems requires simulated Doppler frequency shifts applied to the RF carrier and to the modulation signal frequencies. A description of the ESTL computer-controlled range and Doppler simulation system can be found in reference 6. Additionally, a computerized Real-Time Data Analysis and Predictions System that makes data plots with performance predictions and tolerances and provides permanent data storage (ref. 7) is used to improve productivity by decreasing the time required to assess the performance of the link under evaluation. The ESTL Data Processing and Graphics System is used

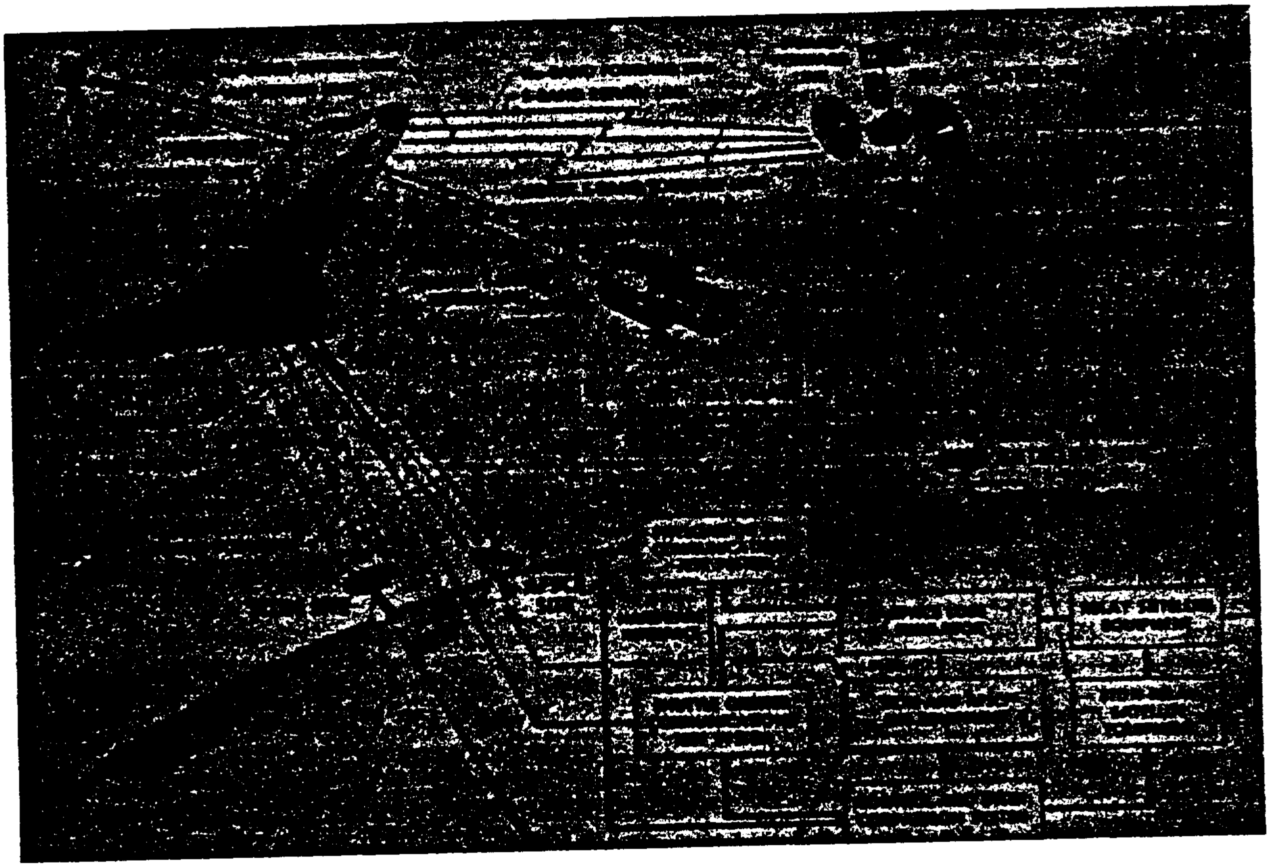

FIGURE 1.- ESTL TEST CONCEPT.

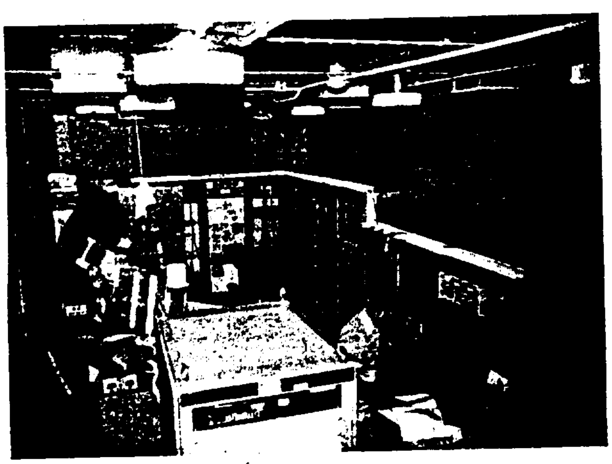

FIGURE 2.- ESTL ORBITER/SPACECRAFT TEST AREA.

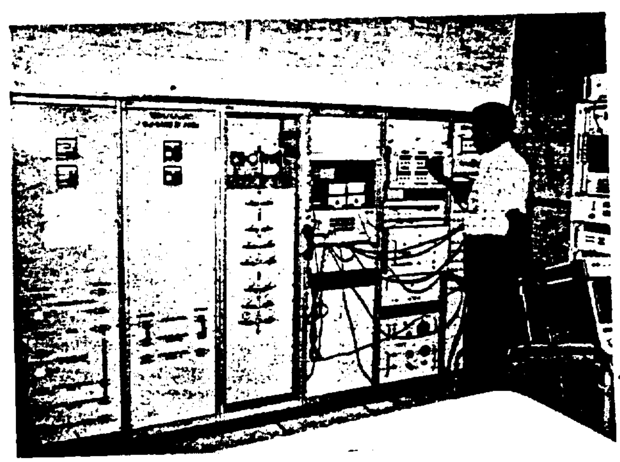

FIGURE 3.- ESTL SPACE LOSS SIMULATOR.

for data acquisition and statistical analysis and generation of digital data required to perform test operations. Techniques that can be used to evaluate early breadboards of telemetry channel performance (without RF receivers) are discussed in reference 8.

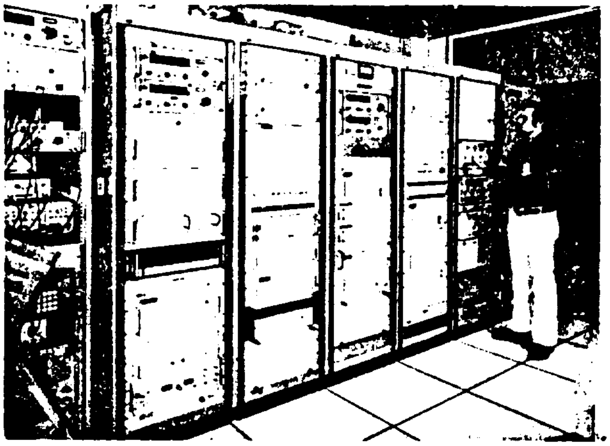

FIGURE 4.- ESTL TDRSS GROUND STATION EQUIPMENT.

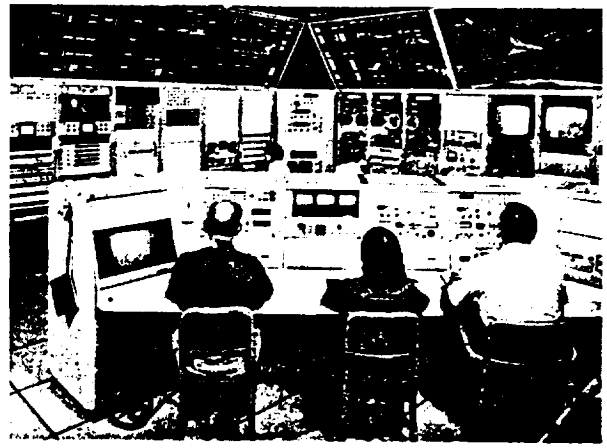

FIGURE 5.- ESTL TEST CONTROL CENTER.

SYSTEM COMPATIBILITY AND PERFORMANCE TESTS

Shuttle communications and tracking systems development testing in the ESTL was divided into two broad categories. The first category, system design evaluation tests, involved the use of Orbiter subsystem breadboards very early in the program. The purpose of these tests was to evaluate proposed communications techniques, hardware, and software implementations; to provide data for Orbiter and possibly network hardware specifications; to determine whether problems existed, evaluate cost-effective solutions to the problems as early as possible, and provide an early assessment of performance capability; and to establish test techniques and criteria for future tests. The second category, system certification tests, involves operational Orbiter and network hardware and results in the certification of the end-to-end systems compatibility and performance. Because of the complexity of the elements involved and the amount of time required to investigate and resolve problems when they occur, it is necessary that this category of testing begin as early as practical in the program. Using prototype Orbiter hardware, these tests are implemented initially to certify that the performance of the system is satisfactory and that the RF communications links between all elements meet program requirements and are ready for flight. The second category of testing is different from the design verification tests in that the space/ground hardware configurations used are flight equivalent. When differences exist between Orbiter prototype hardware and production (flight) hardware, either the prototype hardware is upgraded to be flight equivalent or the production/flight hardware is utilized.

SYSTEM DESIGN EVALUATION TESTS

System design evaluation tests are accomplished using breadboard system hardware configurations. Early tests were accomplished before the hardware procurement specification preparation and continued through the early vendor hardware development phase. Test results were effective in influencing specification parameter values and hardware mechanization/design. The type of tests conducted depended on the particular area of investigation but was generally conducted on an end-to-end basis to investigate system parameters whose interactions are not readily tractable through analytical means or in areas where new math models had been derived but not verified empirically. Particular emphasis was placed on the new, complex, and unproven aspects of end-to-end system compatibility and performance. Figure 6 illustrates the types of sources of breadboard hardware used. The Orbiter breadboard hardware obtained from in-house subsystem laboratories was integrated with a TDRSS (space segment) simulator in a laboratory environment. The integrated breadboard system was then evaluated on an end-to-end performance basis to determine whether any potential Orbiter hardware specification and/or design deficiencies exist. The results of these tests provide GSFC and DOD with performance criteria to establish system performance specifications for Shuttle-unique channels. Critical elements of both the TDRSS S-band and K_u-band single access channels were simulated and evaluated.

The Shuttle S-band and K_u-band system design evaluation tests included both preprocurement specification testing and hardware development support testing. ESTL capabilities include system concept and technique verification, hardware mechanization feasibility, system design requirements development for end-item specifications, and parameter definitions for interface control documents. The following specific examples are discussed to illustrate the nature of system design evaluation testing.

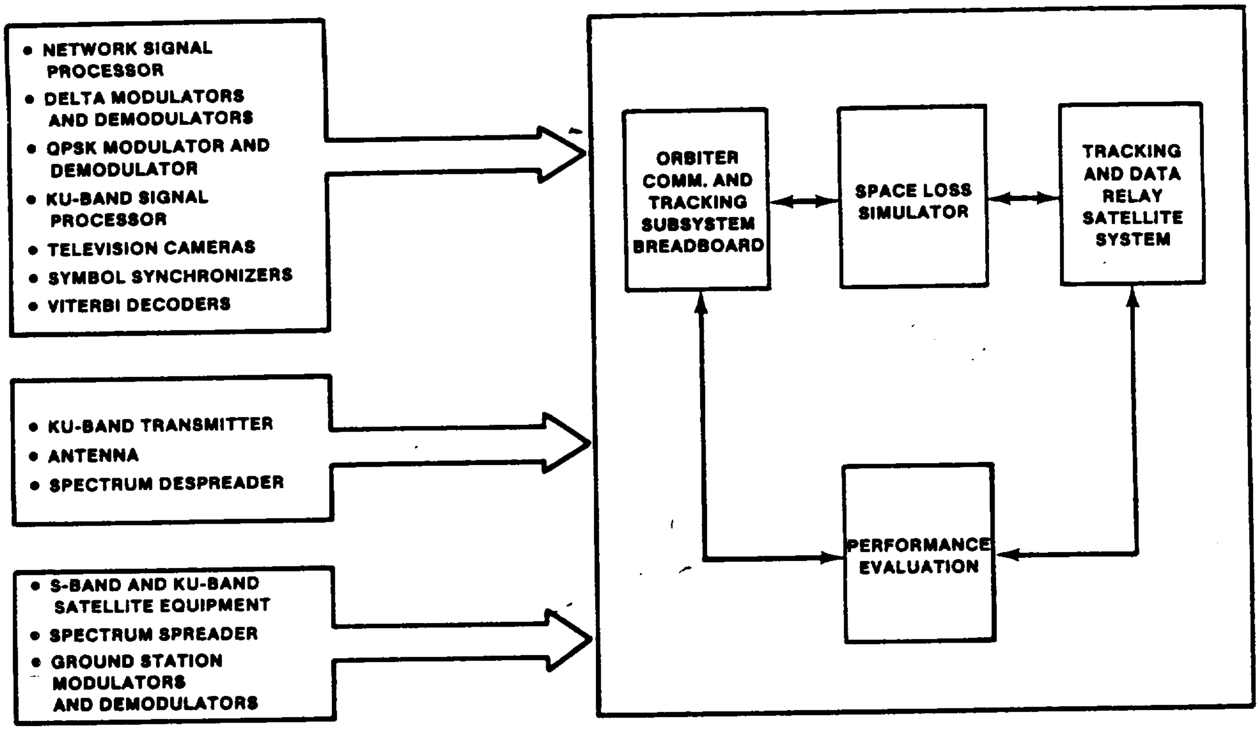

FIGURE 6.- ORBITER COMMUNICATIONS AND TRACKING SUBSYSTEM BREADBOARD SOURCES.

During early system design evaluation testing of the digital voice system, five separate algorithms were evaluated in combination with various audio processing techniques and requirements (automatic gain control, clipping, filtering, levels, etc.), including the effects of convolutional encoding/decoding (error statistics) on voice quality. Frequency modulation (FM) mode parameters were investigated before preparing the procurement specification for the K_u-band hardware. The major areas of investigation included carrier frequency deviations due to television video, receiver bandwidth requirements, subcarrier television interference effects including premodulation and postdetection filtering, quadriphase shift-keyed (QPSK) subcarrier demodulation techniques, and television channel performance criteria (i.e., SNR, response, etc.). Space system elements under evaluation included the wideband signal processor and the K_u-band wideband modulator. The ground system elements under evaluation included the K_u-band wideband demodulator (intermediate frequency (IF) bandwidth), the postdetection filter, and the QPSK demodulator. The system elements and parameters could be accomplished and optimum system specifications established. Results of these tests provided the data used in establishing the frequency deviation for television (±11 megahertz), the premodulation filter specifications for the K_u-band signal processor, and the receiver IF and postdetection filter specifications for the ground station. In addition, it was verified that the television channel performance criteria used for circuit margin calculations provided high-quality video signals.

A second level of design evaluation testing occurs as the hardware design matures. During this phase, the ESTL end-to-end system compatibility was expanded and provided needed support to NASA prime contractors in evaluating vendor impacts resulting from specification deficiencies and/or hardware design deficiencies. Parameters such as frequency deviations, bandwidth requirements, subcarrier interference effects, digital voice quality, coding gain, bit jitter effects, and RF and spread spectrum acquisition probabilities were determined. For example, during S-band FM data performance testing, it was determined that the optimum frequency deviation (Δf) and IF for Manchester and nonreturn-to-zero (NRZ) data formats was 0.62R (Δf), 2.5R (IF) and 0.36R (Δf), 1.5R (IF) respectively, where R is the transmitted data rate.

Of particular interest (because of the high cost impacts associated with a "fix") was the investigation of the effects of data asymmetry on the high data rate (50 Mbps) channel performance during K_u-band tests. The ESTL system testing provided experimental results which, combined with performance simulations and analysis, led to the decision to relax data asymmetry requirements on Shuttle Orbiter data channels. This decision resulted in a significant cost avoidance. The results also indicated that initial analytical predictions of degradation due to asymmetry were highly pessimistic. Subsequently, it was found that analytical results varied significantly if bit synchronizer mechanizations were more exactly modeled. The data asymmetry analytical results (such as dc restoration) are discussed in references 9 and 10. The tests and analysis have shown that a general degradation model for all systems seems impractical. As a result of this activity, the K_u-band hardware vendor was directed to relax the asymmetry specification to 10 percent or less (from the 3 percent or less limitation that had previously been imposed). Relaxation of the specification resulted in a NASA cost savings of several million dollars. Summaries of S-band and K_u-band design evaluation testing are listed in tables 1 and 2 and discussed in reference 4.

During the design evaluation phase, the capability of the ESTL to perform end-to-end system tests proved highly effective in avoiding downstream costly hardware modifications and in allowing specification changes where reasonable. ESTL activities and hardware vendor test capabilities are complementary in nature and result in a high probability that the hardware will be compatible and will meet system performance requirements when integrated with the remaining communication system elements, while minimizing vendor system test equipment capital investment requirements. The net result of this type of system design evaluation testing is a significant program cost avoidance.

SYSTEM CERTIFICATION TEST

Shuttle communications certification tests were different from the system design evaluation tests in purpose, type of hardware used, and depth of testing. The purpose of the system certification tests is to certify that the Orbiter communications systems are ready for manned flight and will support the program requirements. For the most part, prototype Orbiter hardware that was electrically equivalent to space vehicle equipment was used to implement these tests. The use of flight-equivalent hardware ensures that differences between system design verification configurations and flight-type equipment which affect system performance are considered in the certification process and certifies that any problems encountered during the system design verification have been corrected. Shuttle system certification tests were initiated in the second quarter of 1979 and included all of the major space and ground element systems (i.e., GSTDN, AFSCF remote tracking station, TDRSS ground segment, extravehicular astronauts, Spacelab, and five detached payloads). The importance of performing system certification tests cannot be overemphasized. The effects of complex techniques and/or concepts such as unbalanced quadriphase modulation, convolutional encoding/Viterbi decoding, and spectrum spreading and despreading are ascertained. ESTL system test results together with theoretical predictions (analysis and simulation) have been used to characterize the system and to assess end-to-end RF system performance.

Where differences exist between theoretical and measured data, detailed system analysis is initiated. End-to-end system performance is characterized by making system test measurements as listed in table 3. A discussion of performance examples, such as coding gain, Doppler and intermodulation effects, link margins, etc., is beyond the scope of this paper (see refs. 14 to 21); however, some of the significant findings (and problems to be avoided) are summarized in the following paragraphs.

Launch Configuration RF Acquisition

The Shuttle S-band communications system design was intended to provide signal acquisition without interaction by the ground station operators. The Orbiter transponder and the multifunction receiver (MFR) at the ground station were both to begin sweeping about the nominal uplink and downlink

TABLE 1.- S-BAND DESIGN EVALUATION TEST SUMMARY

Issue under investigation	Type of tests	Results/outputs
Delta modulation techniques	Frequency response	Selected modified "ABATE" algorithm
	Output noise spectrum	Determined postdetection BPF response (300 Hz to 2.5 kHz)
	Voice quality	Determined 90-percent word intelligibility $\leq 10^{-2}$ BER
	COMSEC compatibility	Determined compatible with COMSEC

TABLE 1.- Concluded

Issue under investigation	Type of tests	Results/outputs
Convolutional encoding/decoding	Coding gain	Coding gains ≤ 0.3 dB from theoretical were achièvable
	Sensitivity to receiver parameters	Coding gain affected by receiver phase error and IF amplifier limiting
	Error statistics	Compatible with COMSEC - actually decreases sensitivity to channel errors
Television (FM link)	Signal-to-noise ratio and video-to-noise ratio	Determined 26-dB rms/rms SNR requirement consistent with good quality video
	RF spectrum	Determined Δf of 4.5-MHz optimum for direct S-band links
	Postdetection filter optimization	Determined RF spectrum with TV Δf of 4.5 MHz does not result in RFI problem for AF
	Frequency deviation optimization and IF amplifier (predetection)	Determined optimum IF bandwidth for TV approximately 2 Δf, for Δf > 4.0 MHz
Spread spectrum techniques	Adaptive threshold performance	Developed adaptive threshold technique
	Despreading algorithm evaluations	Determined acquisition algorithm sensitivities to system parameters (threshold levels, search, check, and lock stages, etc.)
	Acquisition time	Verified acquisition time predictions
	Tau dither loop evaluation	Developed tau dither loop bandwidth switching technique
	BER degradation due to spreading	Determined despreading degradation < 1.0 dB
FM data performance optimization (NRZ and Manchester formats)	BER sensitivity to Δf and to IF bandwidth	Determined optimum Δf and IF bandwidth for Manchester and NRZ data formats
	Main engine data channel premodulation filter optimization	Premodulation filter characteristics specified
Synchronization strategy evaluation	Data transfer versus bit error probability and voice quality (intelligibility versus data transfer)	Determined data transfer of 80 percent or more at a BER of 1×10^{-1} required to prevent additional voice intelligibility degradation

frequencies, respectively, with data modulating the carriers. The downlink frequency was to be provided by an auxiliary oscillator (AUX OSC) in the Orbiter transponder when the transponder was *not* locked to the uplink signal. When the transponder acquired the uplink signal, the downlink frequency

TABLE 2.- K_u-BAND COMMUNICATION SYSTEM DESIGN EVALUATION TEST SUMMARY

Issue under investigation	Type of tests	Results/outputs
Return link, FM mode (parameter evaluation)	Television signal-to-noise ratio, television quality, and TV/data interference	Determined TV frequency deviation Δf = 11 MHz
		Determined receiver IF BW = 45 MHz
		Determined postdetection filter BW = 4.5 MHz
	Baseband data BER	Specified premodulation filters to minimize subcarrier/TV interference
	Subcarrier channel BER	Determined sensitivity of subcarrier operational data channel to experimental data as a function of experimental data rates. (Worst case approximately 2 dB when experimental data are at same rate or twice the rate of the operational data.)
		Verified voice quality and data bit error probability performance
		Demonstrated feasibility of bent-pipe subcarrier mode
Return link, PM mode (parameter evaluation)	Dual QPSK technique	Verified dual QPSK modulation technique
		Determined signal suppression of low-level channel
	High rate channel BER (uncoded and coded)	Determined system performance at 100, 50, and 25 Mbps for uncoded and coded data
	High rate data asymmetry degradation (uncoded and coded)	Developed asymmetry degradation factor for high data rate channel
	Subcarrier channel BER and high rate/subcarrier channel interference	Verified subcarrier channel bit error probability performance and voice quality
	Bent-pipe channel evaluation	Demonstrated bent-pipe capability in PM mode (subcarrier channel)
Return link, PM mode (parameter evaluation) (cont)	PSK coding gain	Verified coding gain specifications achievable with real world hardware
	Three-channel interplex	Determined interference degradation
		Verified unbalanced QPSK performance

TABLE 3.- SYSTEM TEST MEASUREMENTS

System/function	Test measurement	System/function	Test measurement
Voice	Speech-to-noise ratio Word intelligibility Crosstalk Distortion	Data (command/ telemetry)	Bit error rates Percent information loss Message rejection rates Coding gain Recorder jitter effects
Ranging	Acquisition probability Range data accuracy	Doppler	Doppler accuracy Effects on BER
Acquisition	Costas loop acquisition probability Costas loop acquisition time Spread spectrum acquisition probability Spread spectrum acquisition time Acquisition threshold Mean time to unlock	Television	Resolution Signal-to-noise ratios K-factor Differential phase Differential gain Picture quality

source was to be switched over from the AUX OSC to the voltage controlled oscillator (VCO) and the acquisition process would be completed automatically.

During the uplink acquisition tests, a problem was encountered in that Costas loop acquisition of a signal with modulation on the uplink carrier could be accomplished only at very low signal levels. At signal levels about 49 dB-Hz, the data components in the frequency spectrum became large enough for the transponder to false lock to them instead of the desired carrier. Figure 7 depicts the significant components in the uplink signal spectrum (amplitudes not to scale) for modulation by high and low data rates of 75 kbps and 32 kbps, respectively, and the transponder sweep range. As shown in figure 7, there are a large number of stationary spectral lines within the sweep range of the transponder.

Since a rework of the Shuttle transponder would have been costly and could impact flight schedules, a new acquisition procedure was developed to circumvent the false lock problems. Under the new procedure, the uplink would be transmitted carrier-only (i.e., no data modulation on the carrier) while the downlink would still be transmitted with data modulation present. After a good two-way lock has been achieved, the ground station exciter operator applies uplink modulation.

Tests of the new procedure proved that it circumvented the false lock problem during initial acquisitions. However, once the initial two-way lock has been achieved and modulation applied, if for any reason the uplink should lose lock, it is still likely to reacquire falsely since modulation would be on the carrier during a reacquisition process. In addition, this procedure adds significant ground operator involvement and results in greatly increased total two-way RF acquisition time (fig. 8). Long acquisition/reacquisition times are particularly undesirable during critical mission phases such as ascent and entry when communication dropouts will occur because of unavoidable phenomena such as solid rocket booster (SRB) plume effects, vehicle blockage from the external tank or other Orbiter structures, low-gain portions of the Orbiter antenna patterns, etc.

A new technique was developed and tested (ref. 11) to handle this problem. This technique allows modulation on the uplink during acquisition/reacquisition without ground operator involvement, thereby simplifying acquisition procedures and significantly reducing acquisition time. The technique involves convolutionally encoding the high data rate (72 kbps) time-division multiplexed (TDM) signal to provide a 216-kbps signal. As shown in figure 9, this alone will drive the stronger spectral components out farther. It was found that the strongest spectral components were caused by the voice idle pattern (alternating 1's and 0's) when no voice was being uplinked. Replacing this idle pattern with a random pattern (conventional noise source) effectively eliminates most spectral components except for those at one-half the data rate (i.e., 108 kilohertz, 216 kilohertz, etc.).

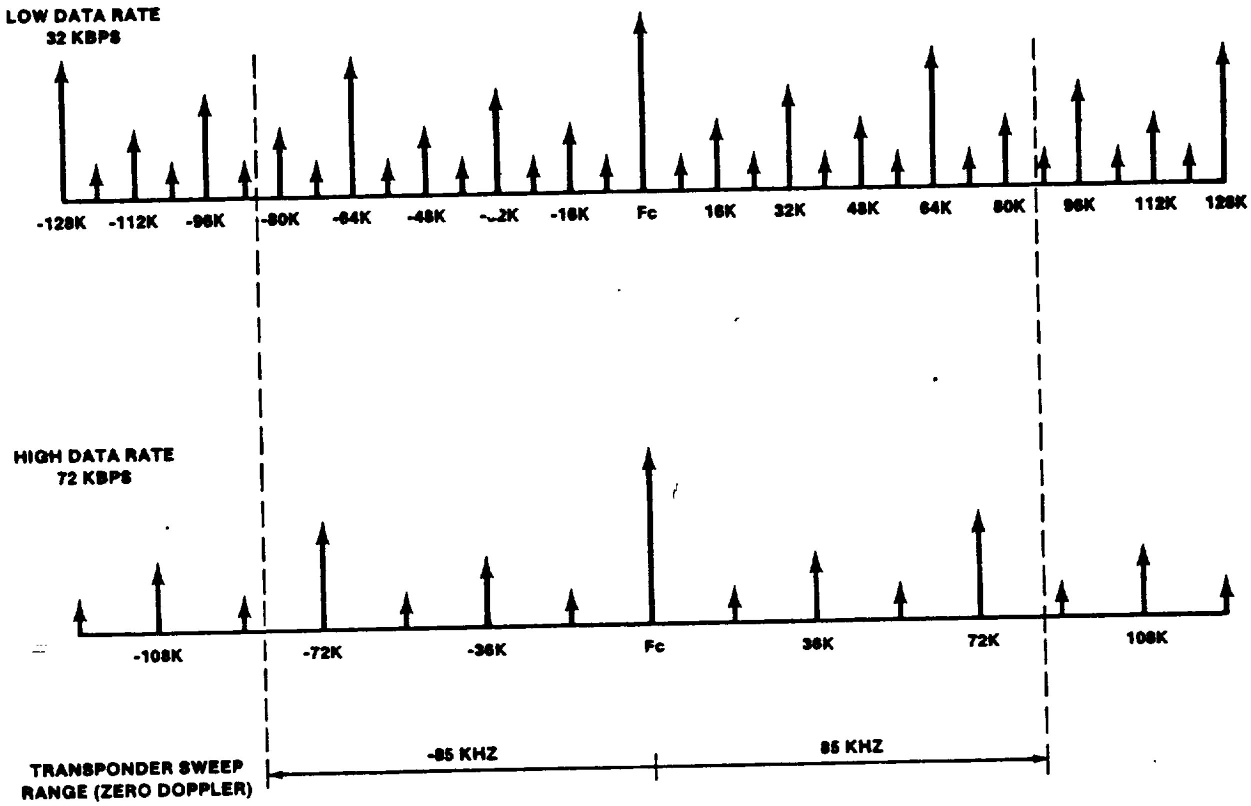

FIGURE 7.- S-BAND UPLINK SIGNAL SPECTRUM.

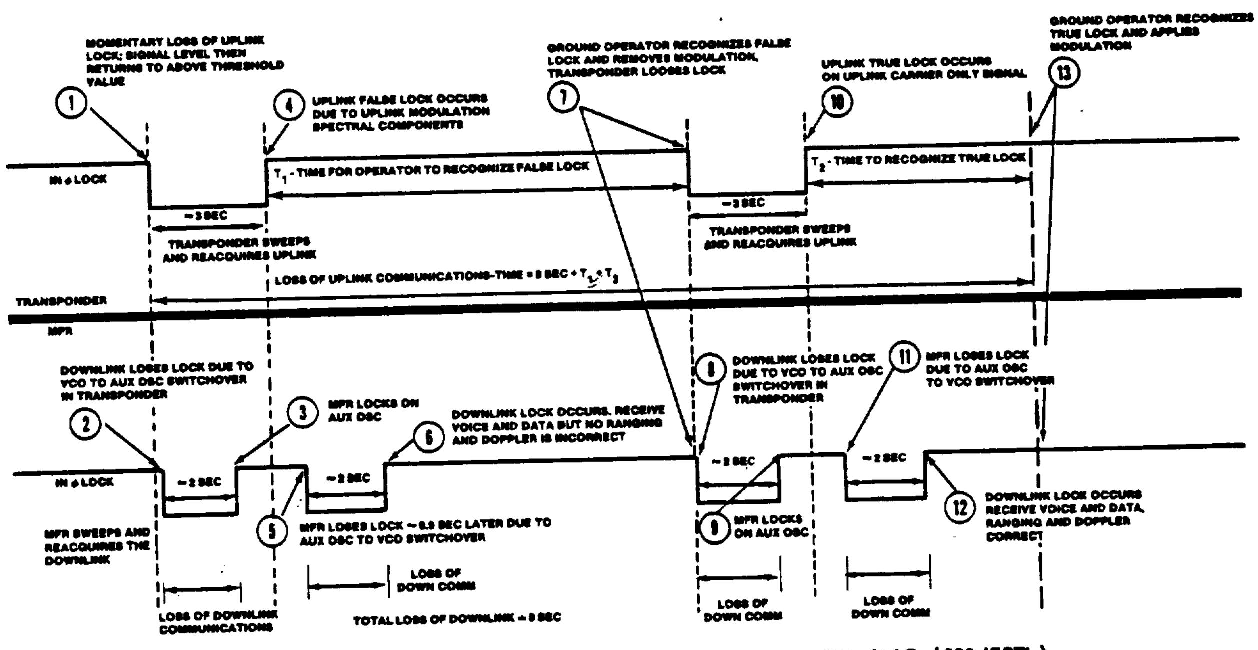

FIGURE 8.- ORBITER-GSTDN TWO-WAY RF REACQUISITION SEQUENCE (JSC/ESTL).

This technique was implemented at the ground stations covering the most critical phase of launch. As expected, the SRB plume effects do cause momentary dropouts. However, the implementation of this

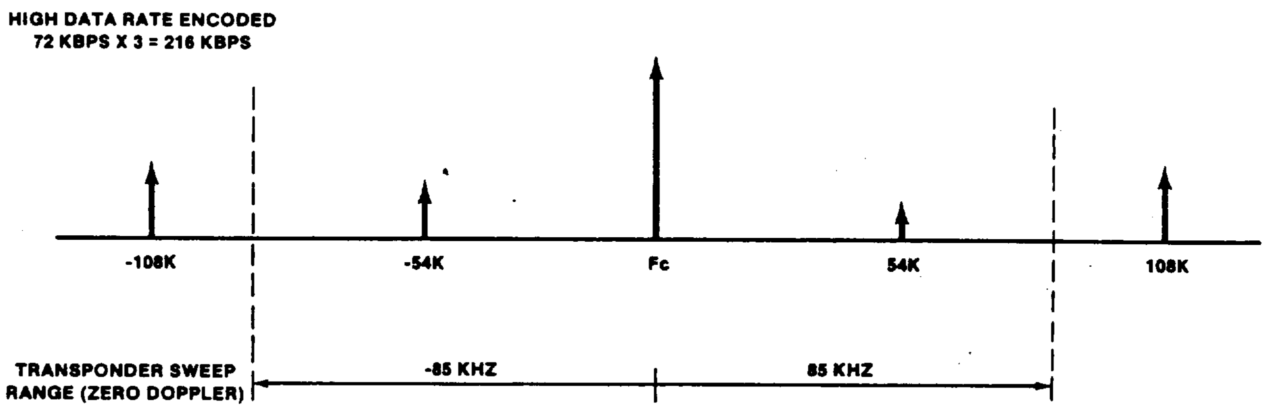

FIGURE 9.- UPLINK ENCODED 72-kbps SIGNAL SPECTRUM.

"noise mode" technique has very effectively prevented the occurrence of false locks during reacquisitions and has minimized the reacquisition time, thereby eliminating excessive loss of data.

Orbiter-GSTDN Ranging Channel Anomaly

A block diagram of the S-band direct link ranging channel is presented in figure 10. As shown in the figure, the range tones phase modulate a 1.7-megahertz subcarrier. This subcarrier is then frequency division multiplexed with the TDM and command data at the input to the transmitter phase modulator. In the Orbiter, the uplink signal is demodulated to a baseband composite in the wideband phase detector. The composite signal is passed through a bandpass filter which is centered at 1.7 megahertz and has a bandwidth of approximately 2 megahertz. The turned-around ranging subcarrier and noise are combined with the downlink TDM data in the transponder. The composite signal then phase modulates the downlink carrier. At the ground station, the 1.7-megahertz subcarrier is detected and then upconverted to 100 megahertz to be compatible with the GSTDN ranging equipment (SRE).

The SRE offers three combinations of tones which can be used to measure range. These combinations are shown in table 4. The high-frequency tone, called the major range tone, is used to obtain the fine (accurate) ranging data and is transmitted continuously after the start of the range acquisition process. The remaining lower frequency tones are used to resolve ambiguities. A more detailed discussion of the range tone transmission sequence is given in reference 13.

The Shuttle ranging system was designed to use the 100-kilohertz major range tone option. Tests showed that the three-sigma range errors were in excess of the specified value of 10 meters. While the three-sigma errors varied with test conditions, the measured errors were as large as 1042 meters when the ranging subcarrier was multiplexed with high rate (192 kbps) TDM data and 59 meters when the ranging subcarrier was multiplexed with low rate (96 kbps) TDM data.

Ranging acquisition probability and accuracy tests were repeated using the 500-kilohertz major range tone option. The three-sigma error was reduced to 20 to 25 meters. However, approximately 2 percent of the acquisition attempts resulted in incorrect correlation of the phase of the 100-kilohertz minor tone and a 300-meter error. Tests conducted with the expected worst-case TDM modulation index of 1.2 radians resulted in three-sigma errors of 1286 meters and a mean acquisition time of 95 seconds. Thus, the tests showed that the ranging system performance was not acceptable.

Further investigation of these problems revealed that the TDM signal itself contained a high-level 100-kilohertz component. The high-rate TDM format consists of 100 minor frames of data per second. Each minor frame contains forty 48-bit bytes. Thus, the bytes occur 4000 times a second. The combination of this 4-kilohertz component at one-half the bit rate (96 kilohertz) results in the high-level spectral component at 100 kilohertz.

The modulation process in which the algebraic sum of the ranging subcarrier and the TDM data phase-modulate the carrier also results in the TDM data phase-modulating the 1.7-megahertz subcarrier. Thus, the spectrum around the 1.7-megahertz subcarrier contains two 100-kilohertz components. One of these components is the desired 100-kilohertz major range tone. The other component is the desired 100-kilohertz component of the TDM data. Since they are derived from different reference oscillators, the phases of the two 100-kilohertz components vary slowly with respect to each other. The amplitude and phase of the resultant sum of these two 100-kilohertz components varied significantly as the relative phases of the two signals changed.

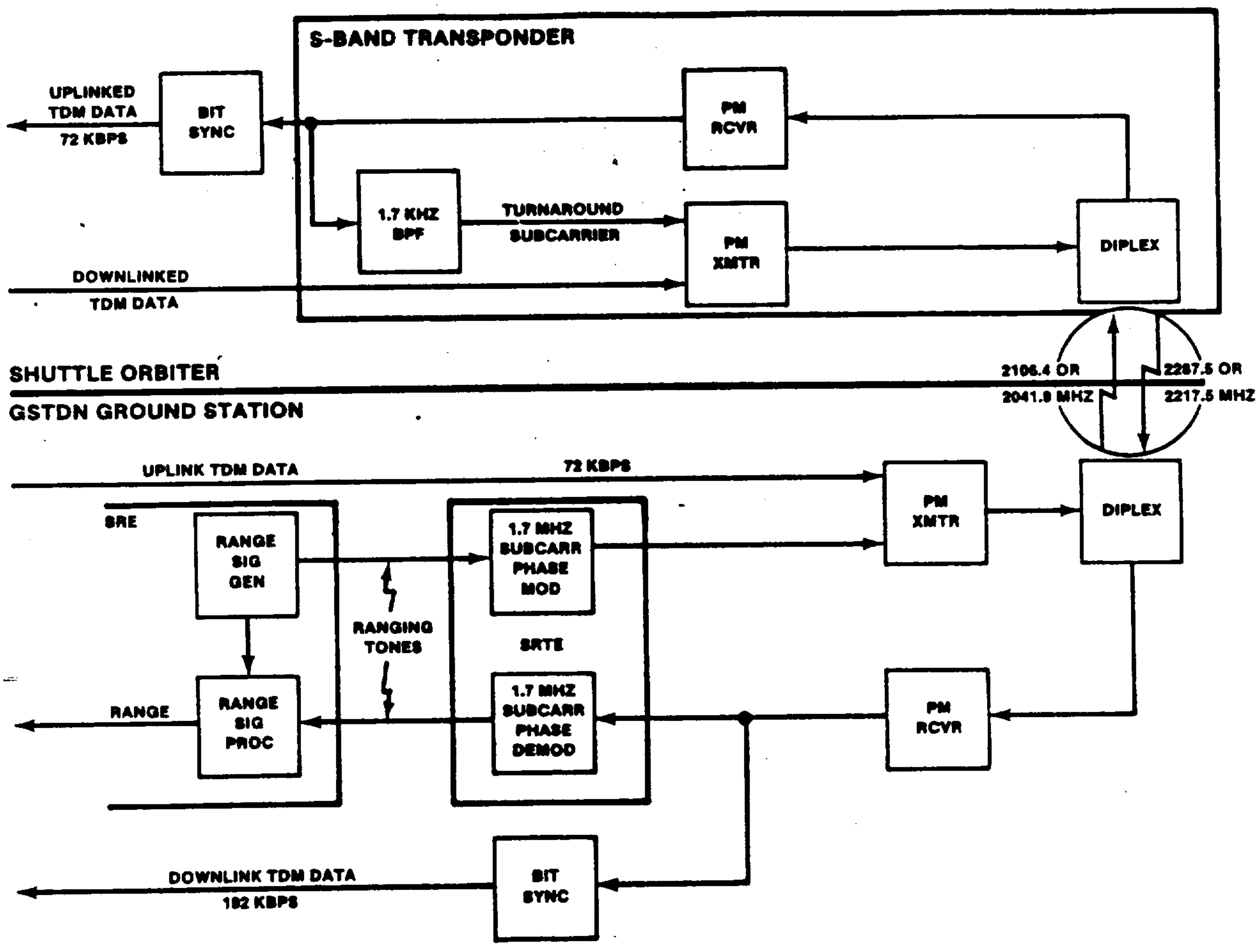

FIGURE 10.- S-BAND RANGING CHANNEL.

TABLE 4.- AVAILABLE RANGE TONE COMBINATIONS

Tone	Combination 1	Combination 2	Combination 3
Major tone	500 kHz	100 kHz	20 kHz
Minor tones	100 kHz 20 kHz 4 kHz 800 Hz 160 Hz 40 Hz 10 Hz	20 kHz 4 kHz 800 Hz 160 Hz 40 Hz 10 Hz	4 kHz 800 Hz 160 Hz 40 Hz 10 Hz

As a result of these investigations, a series of special tests was performed using the GSTDN transmitter and a frequency translator to simulate the downlink signal. Use of this combination allowed the peak deviation of the carrier due to the ranging subcarrier and TDM data to be varied. The reduction of the carrier deviation due to the TDM data to 0.55 radian significantly reduced the three-sigma errors and shortened the acquisition time.

An engineering model of the transponder was modified by reducing the modulation due to the TDM data to 0.55 radian. Tests of this unit showed that the three-sigma error was reduced to approximately 5 meters and the mean acquisition time was reduced to 17 seconds. Based on these results, the Shuttle Program Manager approved a change in the Orbiter S-band transponder design. The results of the tests accomplished with the modified transponder showed that the reduction of the TDM modulation index resolved the range accuracy and acquisition problems.

STS-1 AFSCF/ORBITER INTERFACE INCOMPATIBILITY

The Shuttle STS-1 mission included ground station coverage by the AFSCF remote tracking station located in the Indian Ocean (IOS). During DOD/AF premission readiness testing to functionally verify Orbiter communications system/ground station interfaces, it was observed that it was impossible to transmit Orbiter uplink data from facilities located at Sunnyvale, California, to the Orbiter equipment located at IOS. The problem existed to some extent at both uplink data rates. Bit jitter on the uplink data stream was considered to be the most likely cause of the problem. As a result of the ESTL capability, DOD representatives expedited delivery of affected positions of the IOS Defense Communications System Satellite Control Facility Interface System (DSIS) to supplement the existing ESTL Orbiter/Air Force ground station configuration, for detailed investigation and subsequent resolution of this anomaly. The anomaly was repeated in the ESTL with the DSIS equipment. Test results showed that the problem was caused by the lack of adequate dejitter capability of the dejitter hardware used at IOS. The dejitter hardware was subsequently modified in the laboratory by DOD representatives. Space/ground systems retests performed with the modified dejitter unit provided acceptable performance. ESTL tests confirmed that dejitter capability is mandatory for successful uplink with the Orbiter from IOS and that the DSIS and modified dejitter hardware are not overly sensitive to bit jitter. Return of the DOD hardware and final end-to-end (MCC-GSFC-STC-IOS) forward link integration verification testing were accomplished in time to enable IOS to successfully support the STS-1 mission.

VOICE DISTORTION DUE TO TIME DELAY

Another event that requires special treatment is the potential for voice distortion resulting from differential time delays when two paths are used for redundancy purposes. During Shuttle missions, audio signals are transmitted simultaneously to the Orbiter via UHF and S-band RF links. For example, voice signals routed from the Mission Control Center (MCC) to the Merritt Island Launch Area (MILA) utilize independent paths, resulting in differential delays before transmission. To alleviate the distortion, commonly referred to as the "barrel effect," tests were performed in the ESTL to determine the amount of reduction in the UHF onboard audio level required to substantially reduce the distortion effects but still allow for UHF communications in the event of an S-band failure. These settings were determined and have been successfully used in all Shuttle flights to date.

FORWARD LINK PERFORMANCE DEGRADATION DUE TO RETURN LINK

There have been several cases of the forward link performance being degraded in some manner when the return link transmitter is enabled. For example, during the GSTDN direct link tests, it was found that a degradation of 0.8 decibel in uplink performance occurred when the downlink power amplifier (PA) was enabled (fig. 11). While circuit margins for the direct link were such that an 0.8-decibel degradation would not be a problem, the degradation was critical in the TDRSS mode where the margins were small. Tests were conducted to determine the extent of the problem when the equipment was in the TDRSS mode and to search for its cause.

BER tests were performed for various uplink parameters (frequencies, data rates, spreading, etc.) with the PA in standby, on, and with magnets attached to the preamplifier assembly connectors. The tests with the magnets mounted on the preamplifier connectors were performed because an investigation by the preamplifier assembly vendor had shown that the use of magnets significantly reduced the noise figure degradation which occurs during the use of the PA. The vendor investigation and subsequent investigation by the ESTL were prompted by Alert No. Y1-A-75-01 (ref. 12), issued by the Naval Research Laboratory. The data presented in this alert showed that RF nonlinearities resulting from small quantities of ferromagnetic contaminants (in Kovar hermetically sealed connectors and stainless steel connector shells) caused generation of intermodulation products that can result in substantial performance degradation. This alert also pointed out that the presence of ferromagnetic nonlinearities could be detected by application of an external magnetic field positioned near the connector in question.

Tests were designed to determine what factors were contributing to the degradation and to determine the consequences of this degradation on forward link performance in the TDRSS mode. Three factors were found to be the major contributors to the degradation: ferromagnetic effects, thermal effects, and cable length variations. These contributions to the BER degradation anomaly are sum-

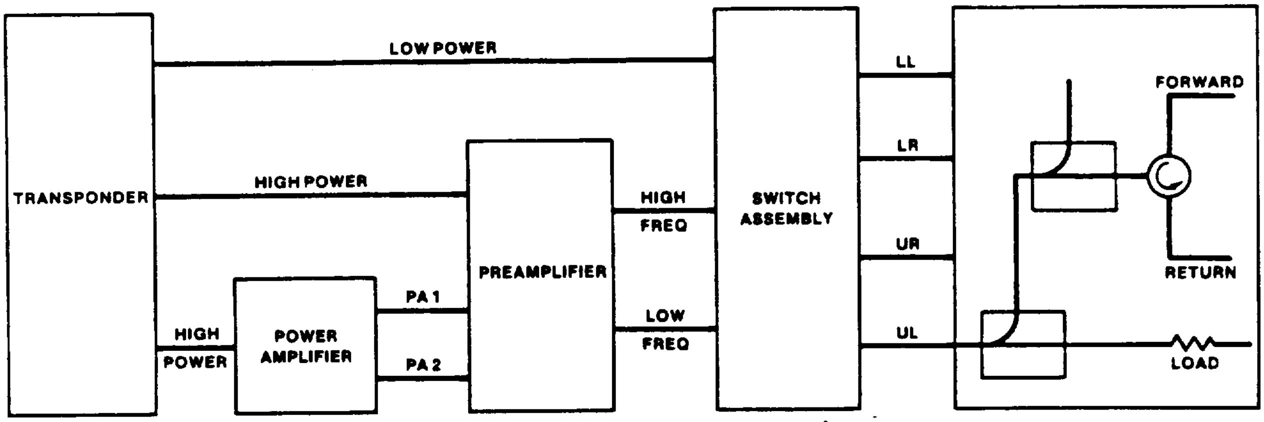

FIGURE 11.- ORBITER S-BAND SYSTEM.

TABLE 5.- BER DEGRADATION CONTRIBUTORS

Effect	Degradation, dB	
	Best case	Worst case
Ferromagnetic	0.4	0.5
Thermal	.1	.2
Cable length variation	0	.5
Unknown	0	.1
Total	0.5	1.3

marized in table 5. As a result of these investigations, the stainless steel connectors on the preamplifier assembly were replaced, resulting in an 0.4- to 0.5-decibel improvement.

A second example of forward link degradation due to the return link occurred during tests conducted on the Orbiter K_u-band system (fig. 12). During these tests, it was found that the forward link BER degraded 10 decibels when the return link transmitter was enabled with full modulation (48 Mbps). The initial assessment by the hardware vendor attributed the cause of this degradation to the failure to properly initialize a set of ferrite switches (fig. 13) when bringing up the system in the COMM mode. These switches are primarily used in the RADAR mode to provide a means of radar transmit/receive blanking to eliminate ambiguities. The "radar xmt safe" control line shown in figure 13 is used to first enable (i.e., place switches in clockwise path) the transmitted pulse, then disable the transmitter (i.e., counterclockwise path). While the transmitter is off, the system will "listen" for the return of the pulse just transmitted. The process is then repeated for the next pulse. The last switch in the set of four is used only in the RADAR mode to provide a path for cases when a very low power radar signal is desired to be transmitted. In this case, the traveling-wave tube (TWT) amplifier is bypassed and the unamplified signal will enter the diplexer through this last switch which will have been set to its counterclockwise position.

In the COMM mode, these switches are to be set in a counterclockwise position, effectively eliminating that path into the second diplexer. The initial assessment by the vendor considered that, if the ferrite switches are not properly set for COMM mode (fully counterclockwise), some wideband RADAR "noise" could be added with the desired COMM signal in the diplexer. This combined signal would then go through the FWD/RTN directional coupler. Although greatly attenuated, some of this combined return link signal could possibly leak through the coupler into the sum receive channel as depicted in figure 13. The bandpass filter is centered around 13.775 gigahertz and is 100 megahertz wide. This

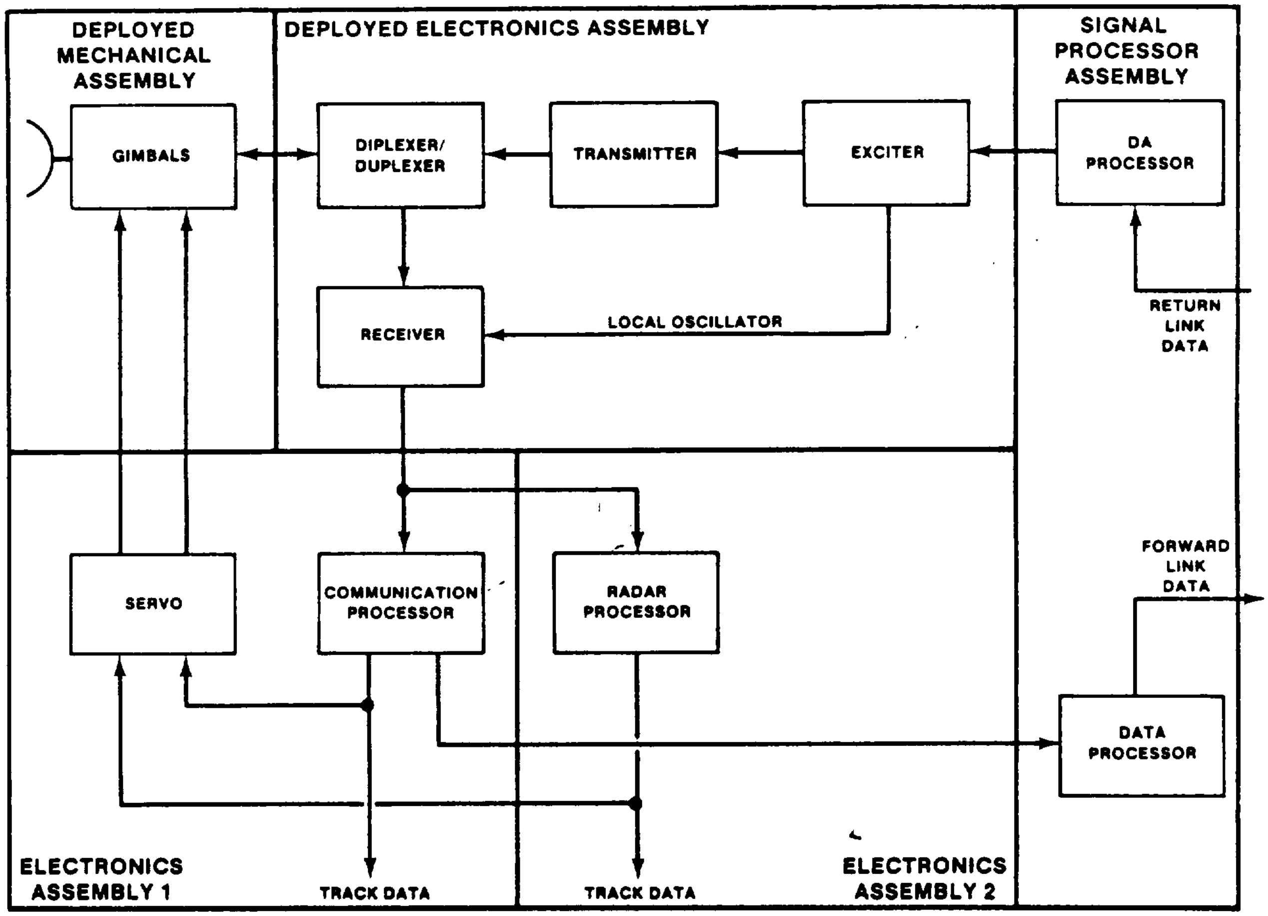

FIGURE 12.- K_u-BAND SYSTEM BLOCK DIAGRAM.

filter would remove virtually all of the narrowband 15.0034-gigahertz return link COMM signal but would pass a portion of the wideband RADAR "noise" and therefore degrade the forward link signal. It was considered that if the ferrite switches were removed or bypassed, the path for the "noise" would be eliminated and thereby the forward link degradation would be circumvented whenever the system is configured in the communications mode. (This modification was to provide a temporary quick-fix to enable the K_u-band system to meet communication system mission requirements; it disabled the high-power radar mode capability leaving the low-power capability which meets the initial radar mode mission requirements.)

Subsequently, the ESTL system was modified by the vendor (ferrite switches were removed). However, ESTL retest of the modified system revealed that only 1.6 decibels improvement was realized (i.e., degradation was reduced to 8.4 decibels at 48 Mbps). Further investigative testing identified the degradation to be caused by a diode signal sampler installed in the deployed assembly waveguide to provide indication of the transmit power level. Removal of this sampler and replacement with a "matched" load for testing purposes completely eliminated the degradation. Subsequent modification by the vendor to all flight units was made thus eliminating the problem.

PAYLOAD INTERFACE TESTING

Space Shuttle Orbiter missions will entail use of tandem communications links for mission operations. The payload links include the payload-to-Orbiter to GSTDN or AFSCF remote tracking station and payload/Orbiter/TDRS configurations. System certification testing is accomplished in the ESTL with particular emphasis placed on the Orbiter/payload RF interface. RF acquisition and data (command and telemetry) tests (table 3) are performed to provide an assessment of the Orbiter capability for a specific payload. The ESTL payload test capability is illustrated in figure 14. After completion of ESTL RF tests, and depending on new, unproven, or untested designs, joint Shuttle Avionics

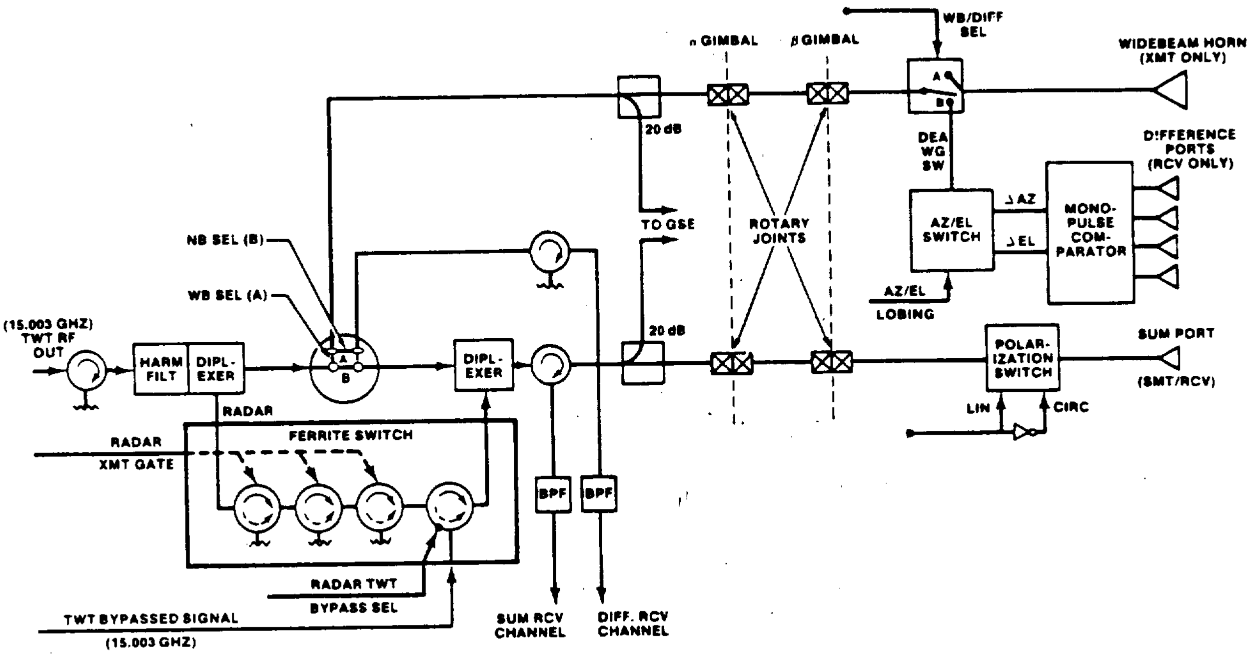

FIGURE 13.- K_u-BAND DEPLOYED ELECTRONICS ASSEMBLY FRONT-END DIAGRAM.

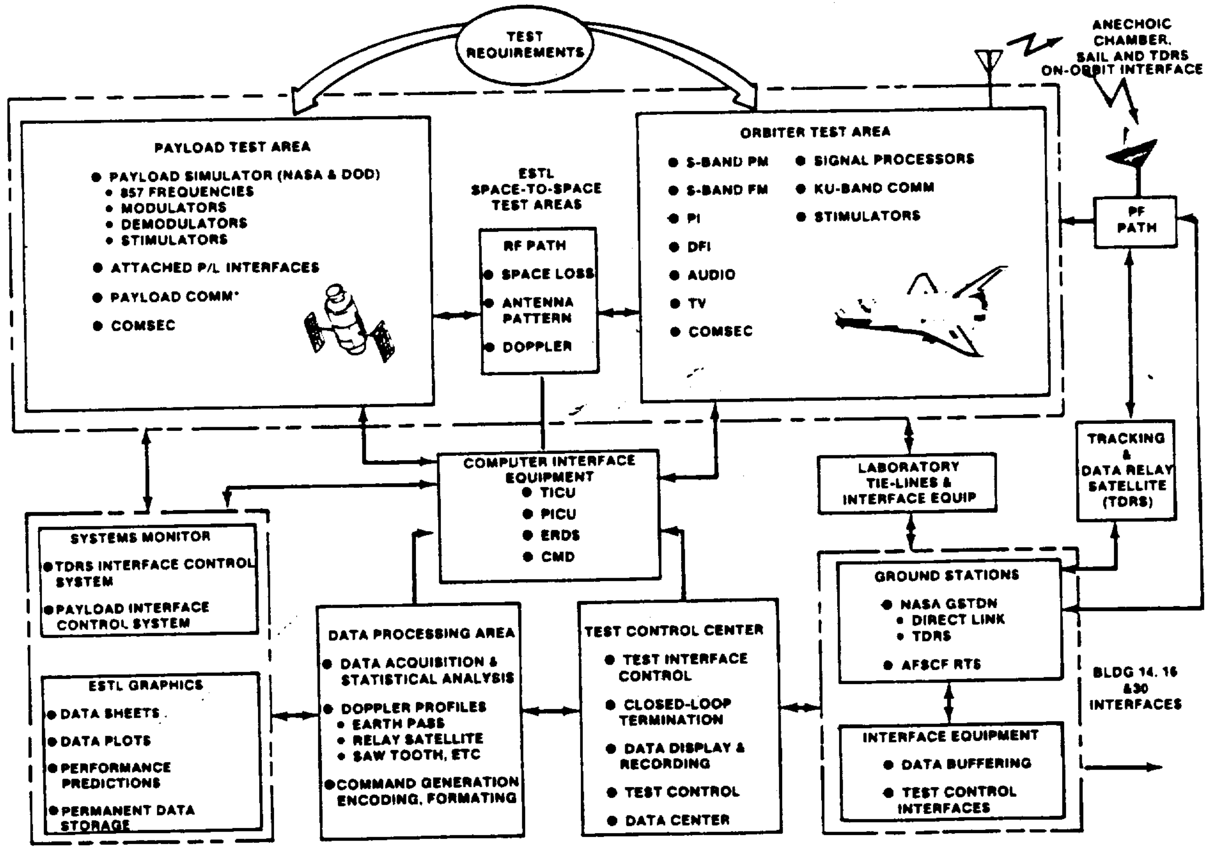

FIGURE 14.- ESTL PAYLOAD TEST CONFIGURATION.

Integration Laboratory (SAIL)/ ESTL tests are performed to provide an evaluation of the hardware/software and external RF interface capability. (Joint SAIL/ESTL tests are functional.)

To date, five payload RF communications configurations (including the Spacelab and DOD/Inertial Upper Stage) have completed the system certification test phase. Several problem areas and significant findings were identified as follows.

1. The Orbiter payload signal processor was susceptible to false-lock to telemetry data. Design changes were made and a retest verified the fix.

2. Payload transponders that did not incorporate anti-side-band lock features require the Orbiter to transmit an unmodulated carrier during RF acquisitions. This is an operational constraint that is particularly bothersome whenever a momentary loss of lock occurs such as during an antenna pattern null or blockage.

3. Test results show that some payload transponders when operating in the coherent mode (and no uplink) are susceptible to AUX OSC/VCO intermittent switching (causing Orbiter payload interrogator to lose lock) if the ranging channel is enabled.

4. There is a high probability of return link false lock on turned-around forward link data when ranging is enabled.

5. Sufficient Orbiter (onboard) crew displays of forward link status (AGC, static phase error, data good, etc.) are required to achieve and maintain good two-way acquisition. Additional information can be found in references 22 through 25.

ESTL OPERATIONAL SYSTEMS TEST

The third phase of ESTL testing involves operational configurations and/or concepts. Figure 15 depicts a series of end-to-end operations integration tests, performed in cooperation with GSFC, of the integrated Space Shuttle Orbiter/Tracking and Data Relay Satellite (SSO/TDRSS) communication links utilizing SSO communications hardware, the operational TDRSS, with an on-orbit TDRS. These tests are to be accomplished after the Orbiter-TDRS basic certification testing has been completed in the ESTL and after Mission Control Center (MCC), Network Control Center (NCC), and MCC/NASA Ground Terminal (NGT) validation testing but before the first mission use of the TDRSS.

As depicted in figure 15, the SSO S-band and K_u-band communications subsystems will be located in the ESTL. The TDRSS Ground Terminal, located at White Sands, New Mexico, and the TDRS-A satellite, in geosynchronous orbit, constitute the first "satellite hop" configuration. The communications links are completed by the second "satellite hop" from White Sands to the JSC/MCC and GSFC/NCC by a Domestic Communications Satellite. This series of tests constitutes a final demonstration of the overall Shuttle/TDRSS operational readiness before first mission utilization. Primary test objectives include determination of RF acquisition tracking thresholds, demonstration of S-band two-way Doppler tracking capability for carrier-only and modulated-carrier conditions, determination of data, bit error rates for S-band and K_u-band as a function of total received power, and demonstration of the capability to accommodate the data channels (command, telemetry, and digital voice) of both the forward and return links. A description of tests can be found in reference 26.

SYSTEM TEST EFFECTIVENESS

During the Shuttle development phases, the ESTL results made significant impacts on hardware design parameters and specifications. As system hardware design progressed, system certification test results were utilized to avert serious program impacts. For example, as noted earlier, significant cost avoidance was accomplished by providing an understanding of the jitter characteristics affecting performance of the IOS DSIS link. Additionally, modification of the S-band transponder by reducing the TDM modulation index resolved unacceptable range accuracy and acquisition problems. The effectiveness of system performance and compatibility testing was well proven, both as a cost-effective system development tool and as a highly accurate system performance assessment method. The performance assessments achieved by these tests provide an engineering data base necessary to accomplish cost-effective mission anomaly resolutions, establish mission constraints, and/or evaluate proposed system updates/additions. At the conclusion of system certification tests for Shuttle, the performance capabilities of each communications link will be well documented, available link margins will have been measured, incompatibilities will have been identified, and alternate solutions developed to resolve the incompatibilities implemented.

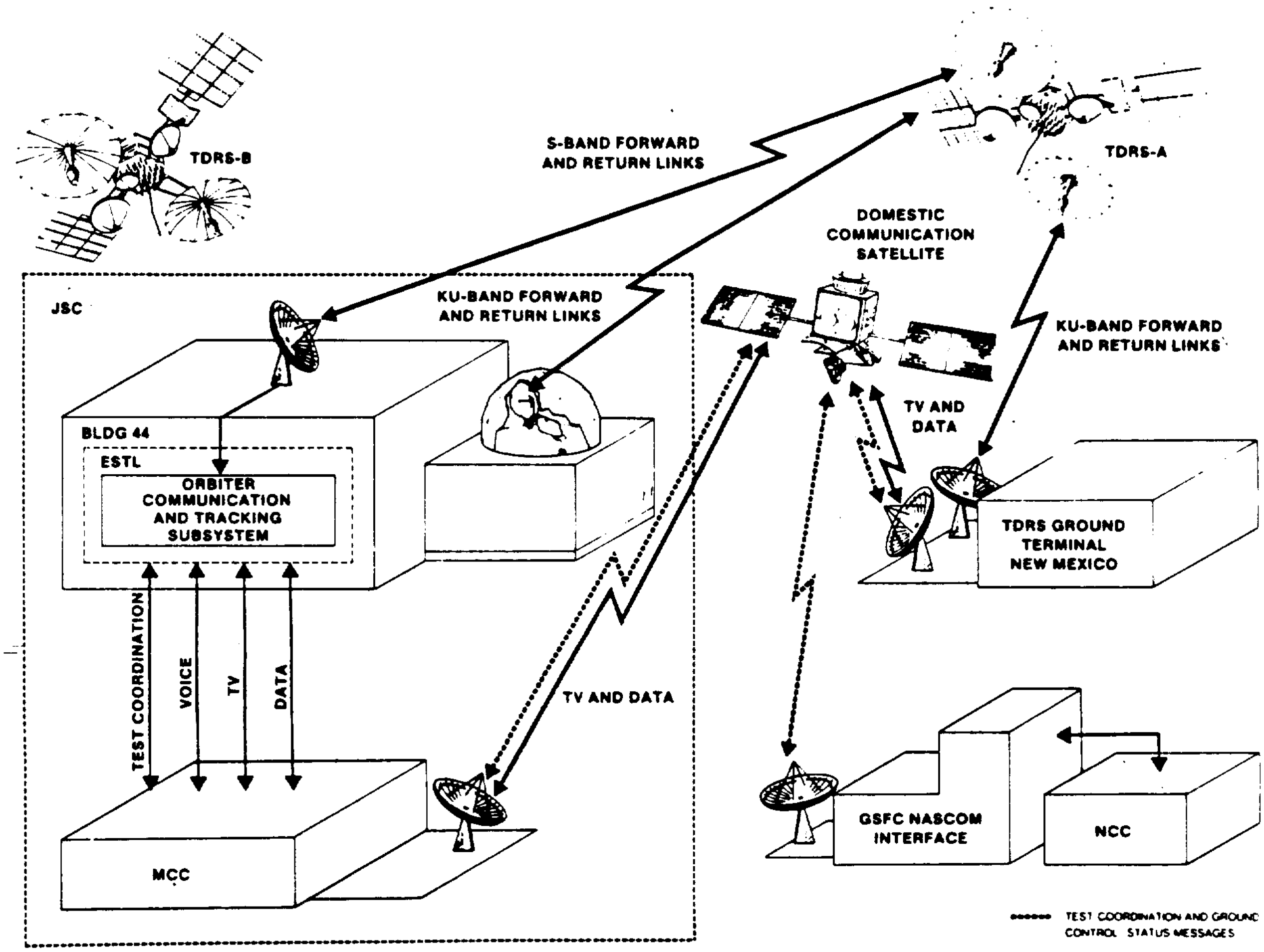

FIGURE 15.- TDRS INTERFACE TEST CONFIGURATION.

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