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SHUTTLE K_u-BAND COMMUNICATIONS/RADAR TECHNICAL CONCEPTS

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ABSTRACT

Technical data on the Shuttle Orbiter K_u-band communications/radar system are presented. The emphasis is on the more challenging aspects of the system design and development. The technical problems encountered and the advancements made in solving them are discussed. The radar functions are presented first. Requirements and design/implementation approaches are discussed. Advanced features are explained, including Doppler measurement, frequency diversity, multiple pulse repetition frequencies and pulse widths, and multiple modes. The communications functions that are presented include advances made because of the requirements for multiple communications modes. Spread spectrum, quadrature phase shift keying (QPSK), variable bit rates, and other advanced techniques are discussed. Performance results and conclusions reached are outlined.

INTRODUCTION

Two important functions that the Orbiter must perform while orbiting the Earth are to detect and track other objects (targets) and to communicate with Earth via the Tracking and Data Relay Satellite (TDRS). Target tracking is required to support rendezvous operations; communications are needed to provide data, voice, and television transfer. By the time these program requirements were finalized, the Orbiter configuration had been set and the K_u-band system design had to be made compatible with it. As a result, the deployed assembly (DA) was mounted in the payload bay between the payload envelope and the payload bay doors (fig. 1). Since rendezvous target tracking is a short-term operation, it made possible the combining of the radar and communications functions in one system and thereby saved weight and cost and minimized impact to the Orbiter. The challenges and innovations in the K_u-band system are due in large part to the fact that the system had to meet two sets of complex and sometimes conflicting requirements.

FIGURE 1.- DEPLOYED ASSEMBLY MOUNTED IN THE ORBITER PAYLOAD BAY.

An overall diagram of the K_u-band system is shown in figure 2. Note that the system tracks targets and communicates, but not simultaneously. The block diagram shows that the system consists of the DA, electronic assembly 1 (EA-1), electronic assembly 2 (EA-2), and the signal processor assembly (SPA). Display, control, and electrical power interfaces are not shown.

The radar challenges/design approaches are presented first, followed by the communications discussion. Emphasis is given to technical advancements, and only limited details about the K_u-band system are presented. Further information can be found in the references given at the end of this paper.

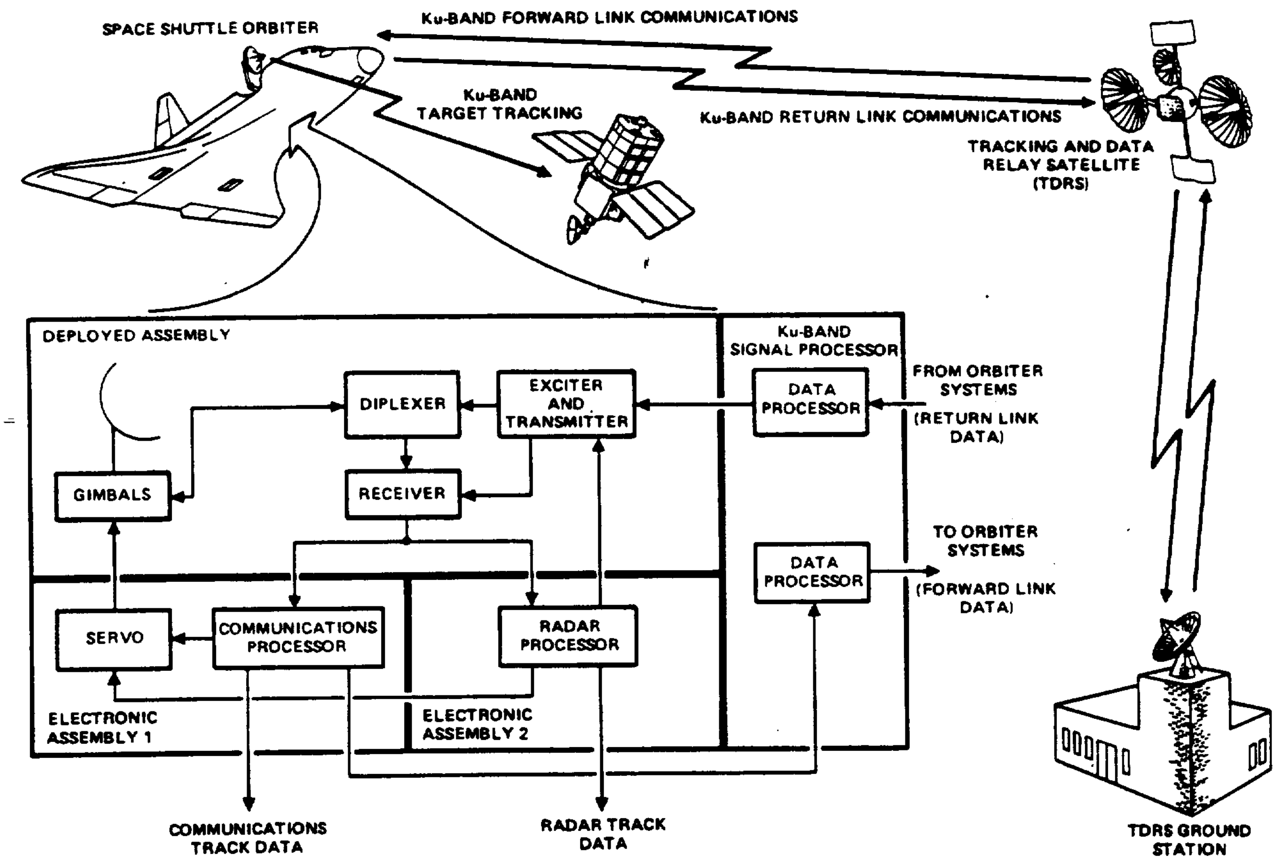

FIGURE 2.- ORBITER K_u-BAND RADAR/COMMUNICATIONS SYSTEM.

K_u-BAND SYSTEM DESIGN

GENERAL

Early in the K_u-band system design phase, it was determined that the functions common to radar and communications that could use common hardware were transmission, reception, and antenna control. The system, therefore, has in common a traveling-wave tube (TWT) transmitter, a receiver, an antenna, an antenna controller, and microwave components (refs. 1 and 2). The TWT transmitter provides both continuous-wave (CW) and pulsed operation. The TDRS dictates a forward link (K_u-band receive) frequency of 13.775 gigahertz and a return link (K_u-band transmit) frequency of 15.0034 gigahertz. The radar center frequency is 13.883 gigahertz, which allows common use of receiving circuits and the TWT.

The common components (receiver, transmitter, antenna and servo, and microwave components) must satisfy diverse requirements. Specific technical challenges resulting from these requirements were in the development of an efficient TWT; a narrow beam antenna with a lightweight, high-gain, paraboloidal reflector and monopulse feed; and a multifunction servo system to accomplish search, acquisition, and track during either radar or communications operation.

The requirements for high TWT efficiency at 15.0034 gigahertz CW and variable duty cycle pulse operation at 13.883 gigahertz resulted in the development of a permanent periodic magnet focused helix TWT with three stages of depressed collectors. The TWT provides 55 to 60 watts of radio-frequency (rf) power over the frequency band from 13.75 to 15.1 gigahertz with a gain of greater than 40 decibels. The electron gun is designed to provide a 65-milliampere beam at 7 kilovolts. A modulating anode is incorporated to switch the beam current on and off. A dual-pitch helix is used to provide optimum rf characteristics in both the radar and the communications bands with low distortion. A beam scraper is introduced between the electron gun and the input end of the helix to provide thermal protection for the helix in the case of power supply malfunction or electron gun arcing. The TWT is 14 inches long, 3.5 inches wide, and 2.7 inches high and weighs approximately 5.5 pounds.

The main technical challenges encountered in the development of the K_u-band antenna system were (1) minimum weight and restricted stowage volume, (2) space environment, (3) right-hand circular polarization for communications and linear polarization for radar, (4) angle search, acquisition, and tracking, and (5) minimum losses. These challenges were met in the design of the DA (refs. 2 and 3).

The DA consists of the antenna, a gimbal mechanism, and all electronics that are required to be near the antenna. Transmission line losses at this frequency made it necessary to locate all rf (K_u-band) functions near the antenna. Therefore, the DA contains all electronics to convert from intermediate frequency (i.f.) to rf and to amplify and transmit at the K_u-band frequency, along with the front end of the receiver, the low noise amplifier, and the down converter. The location selected for the DA led to two constraints on the antenna. First, the antenna depth was restricted to approximately 14 inches. Second, a boom and a deployment mechanism were required to obtain a maximum field of view. The stowage space constraint led to an edge gimbal attachment for the antenna dish. Therefore, the resonant frequency of the boom/gimbal/dish varies with pointing angle, as does the dish inertia. A switchable-bandwidth servo was implemented to achieve stability while meeting the radar search requirements.

The antenna is a prime-fed paraboloidal reflector and uses a five-element monopulse feed with a monopod feed support. The 36-inch parabola has a focal length to diameter (f/D) ratio of 0.28 and is constructed of epoxy-impregnated graphite tape formed over four main supporting ribs. The graphite construction provides excellent thermal characteristics and results in a very stable and lightweight antenna. The unique monopulse feed uses a crossed-probe-fed, dielectrically loaded waveguide horn as a sum channel element and four resonant slots as difference channel elements. The sum port transmits and receives either linear or right-hand circular polarization (selected by system mode of operation) and is independent of the monopulse tracking function. This five-feed approach provides minimum communications system signal loss since the monopulse comparator is only associated with the difference channel elements and is not in the transmit or sum channel signal paths. The monopulse comparator combines the difference channel signals to produce azimuth (ΔAZ) and elevation (ΔEL) error signals. These error signals are phase coded and time division multiplexed before they are added to the sum channel.

Another engineering challenge resulting from the location constraint was antenna sidelobe levels. Design of a short-focal-length antenna, with a focal-point feed to minimize weight on the gimbal, was required. The initial design consisted of a 4- by 4-inch feed, which included the monopulse bridge. The sidelobe levels were much too high, on the order of -17 decibels for circular polarization and -15 decibels for linear polarization. The monopulse bridge was moved and the feed was redesigned into a 2- by 2-inch package. This change resulted in sidelobe levels of about -21 decibels for circular polarization. Even these reduced sidelobe levels may not eliminate all acquisition difficulties.

The combination of boom length and deployment mechanism (one-axis turntable) had a significant impact on the angle servo system design. Resonant frequencies in the 8- and 12-hertz region severely limited the stable bandwidth of the servo. The first design was found to be unsatisfactory. The radar search requirements required a wide bandwidth, whereas stability indicated a narrow bandwidth. Other challenges surmounted in the development of the K_u-band servo system were (1) wide angular coverage, (2) adaptive response dependent on search, acquisition, or track function, (3) antenna scanning to provide coverage and sufficient time on target for detection, (4) multimode capability providing for designation by the general-purpose computer (GPC), manual slewing, scanning variable sectors at variable rates, operation as an autotrack system, inertial or body stabilization, and control by an internal system microprocessor, and (5) providing coordinate transformations between the antenna and the Orbiter coordinate axes.

To obtain the nearly 4π steradians of spatial coverage using a two-axis elevation over azimuth gimbal system, the servo provides rapid whiparound in azimuth whenever the elevation or azimuth mechanical limits are approached. These whiparounds must be accomplished in minimum time because spatial coverage for moving targets is lost whenever whiparound occurs.

A passive thermal design was implemented that is adequate for "beginning of life" surface conditions. The design includes silvered Teflon on parts of the DA. This surface is rather delicate and requires careful handling of the antenna assembly. A replacement schedule for the thermal surface will be developed as the system is used.

RADAR DESIGN

To perform the radar function, the K_u-band system is required to do the following.

1. Search for, detect, and track passive (nonaugmented) and active (transponder-augmented) targets
2. Measure and provide target data (range rate, range, angle rates, angles) to the Orbiter for use in rendezvous operations
3. Provide for signal flow to and from the Orbiter for displays and command/control

Table 1 summarizes the radar performance requirements. The main challenges arise from the angle rate and range rate accuracy requirements for the passive target case.

TABLE 1.- K_u-BAND RADAR REQUIREMENTS

Parameter	Passive target (1 m^2 cross section)	Augmented target
Search, acquisition, track volume:		
Angle search, acquisition	±30°	±30°
Track	Orbiter obscuration	
Range	100 ft to 12 n. mi.	100 ft to 300 n. mi.
Probability of detection (FAR = 1/hr)[a]	0.99	0.99
Range accuracy, 3σ	80 ft or 1%	
Velocity accuracy, 3σ	1 ft/sec	
Angle accuracy, 3σ	8 mrad	
Angle rate accuracy, 3σ	0.14 mrad/sec	

[a]False alarm rate.

The angle tracking servo is shown in figure 3. The servomechanism includes rate integrating gyros, gimbal torque motors, shaft encoders, a microprocessor, and other elements. The antenna position and motion is controlled by the Orbiter GPC, by the astronaut, or (when the servo loop is closed) by the target's relative motion. A spiral scan is used to find the target. When the loop is first closed, a type 2 transfer function with a short time constant is used to rapidly reduce the angle error. A switch to a longer time constant type 2 servo then provides the required angle rate and position accuracies. The servo time constants are switched as the range changes to meet the dynamics and accuracy requirements.

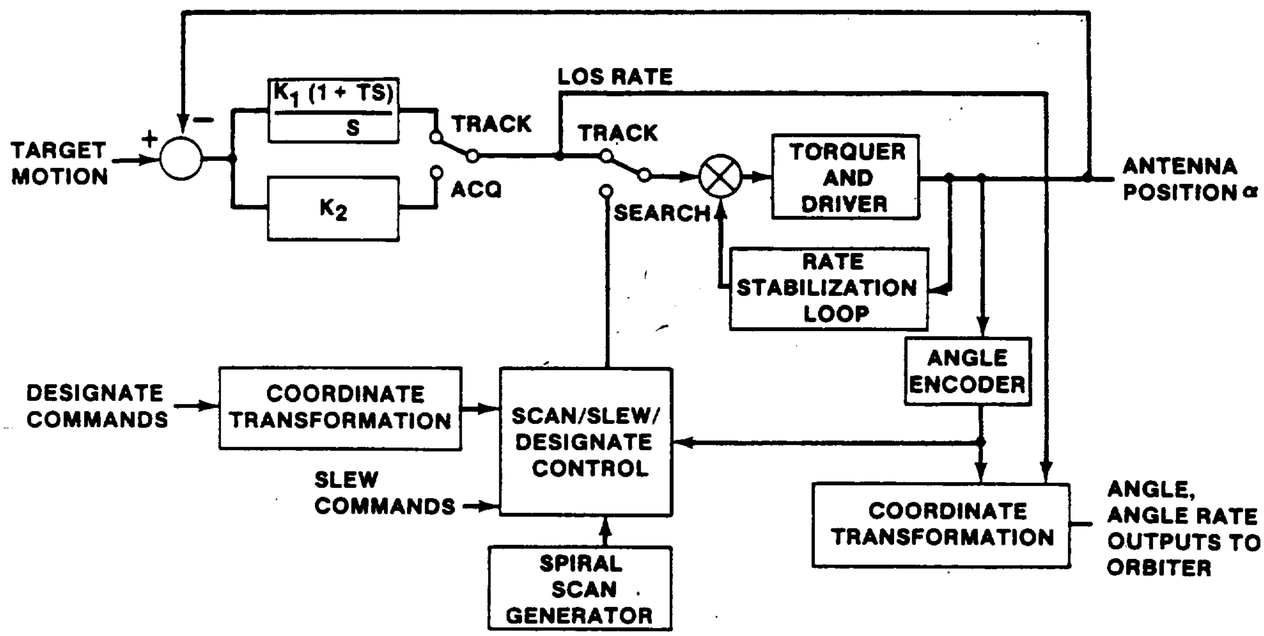

FIGURE 3.- ANGLE TRACKING SERVO BLOCK DIAGRAM.

The K_u-band radar uses a number of advanced techniques to obtain optimum performance (refs. 4 and 5). Frequency diversity (five frequencies) is used to obtain increased detection range. Pulse Doppler techniques provide range measurement and the required range rate accuracy. The transmitted pulse repetition frequency (PRF) and pulse width are changed with range to maximize detection probability and range rate accuracy. To allow for tracking at short ranges and reduce the probability of sidelobe acquisition, a TWT bypass mode is provided. Fourier transform filtering and logarithmic discriminant techniques are used to determine the Doppler frequency (range rate), the angle rate, the angle position, and the range.

RADAR TESTING

Various tests of the K_u-band radar have been conducted. Successful testing during STS-7 was performed using the SPAS-01 payload as a target. Detailed tests, using dynamic targets, are to be conducted at the NASA Lyndon B. Johnson Space Center (JSC) White Sands Test Facility (WSTF) later this year to obtain performance and error model data. Some early system data obtained by Hughes and Rockwell (K_u-band and Orbiter contractors) while tracking a helicopter are shown in figure 4. A reference system was not used; hence, the accuracy of such data remains to be determined by the WSTF tests.

COMMUNICATIONS DESIGN

To meet the communications requirements, the K_u-band system in the communications mode receives/transmits signals from/to the TDRS (table 2) (refs. 6 and 7). This capability provides a significant increase (relative to earlier missions) in the percent of time during which the Orbiter is in communications contact with the ground. This capability also meant that the K_u-band system design *(ref. 2)* had to meet a number of advanced requirements including those arising from (1) mutual acquisition of the narrow-beam K_u-band and TDRS antennas, (2) reception and processing of a spread-spectrum signal,

(3) processing, modulating, and transmitting several data sources, and (4) synchronizing with high-rate payload data routed over Orbiter cables.

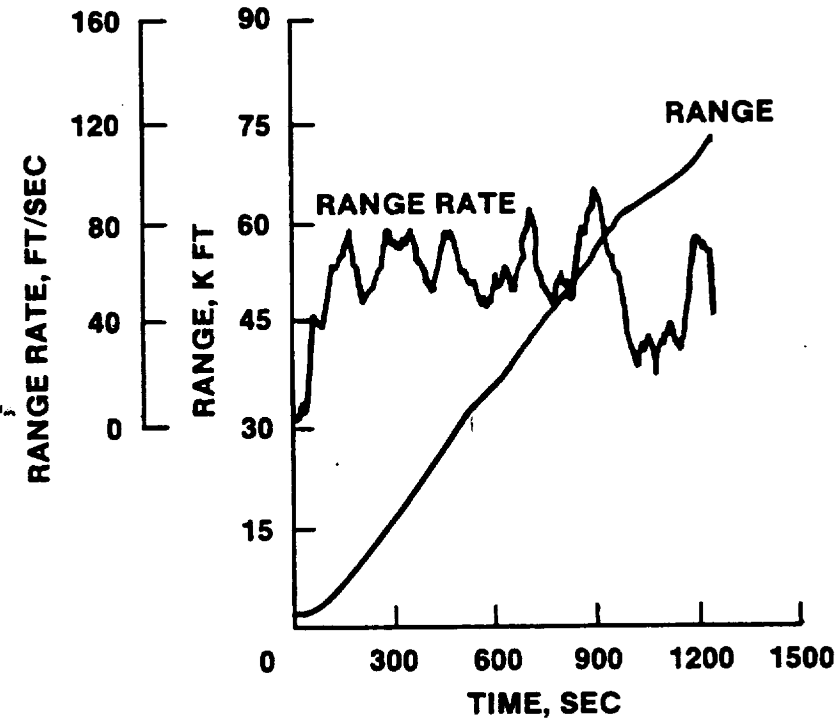

FIGURE 4.- RADAR TEST DATA, HELICOPTER TARGET.

The K_u-band forward link design was influenced by the need to be compatible with the S-band link (ref. 8) resulting in the bit rates shown in table 2. High antenna gains and the relatively low maximum bit rate of 216 kbps eased the design difficulties.

TDRS signal acquisition involves the following: (1) TDRS open-loop pointing at the Orbiter, (2) Orbiter acquiring the forward link by doing a spiral scan, (3) Orbiter transmitting the return link, and (4) TDRS acquiring the Orbiter return link and pointing with a maximum of 0.5 decibel pointing loss. Several aspects of this acquisition procedure proved challenging. First, because the TDRS first points its antenna at the Orbiter, there is a large dynamic signal amplitude range at the K_u-band system. Second, because of the uncertainty of K_u-band pointing at the TDRS, a spiral scan is required to find the TDRS. Finally, the dynamic range of the TDRS signal level, the Orbiter antenna sidelobe levels, and Orbiter monopulse tracking loop pull-in characteristics are such that the Orbiter antenna could stop in the scan before pointing its main beam at the TDRS. This problem has been solved by transmitted power control by the TDRS.

Another major design challenge involved bit synchronization of the high-rate payload data (refs. 9 and 10). The payload data rate can vary from 2 to 50 Mbps and can have significant data asymmetry (ref. 11). In addition, the Orbiter cables from the payload to the K_u-band system introduce risetime degradation and amplitude modulation (ref. 12). The first K_u-band interface circuit was found to have a range of clock/data phase offsets and to make unstable bit detections at high data rates. A redesign was also found to have inadequate margins for bit detection. Finally, an adaptive threshold bit synchronizer was designed and extensively analyzed to provide adequate performance margins with respect to clock/data phase offset, amplitude, transition time, and data jitter.

Table 2(b) shows that the return link communications design is more complex than the forward link. To transmit TV signals (Mode 2), frequency modulation (FM) was selected because of its maturity relative to digital techniques. To allow simultaneous transmission of TV and two channels of lower rate digital data, the TV signal frequency modulates at baseband, and the digital data modulate a subcarrier using unbalanced quadrature phase shift keying (UQPSK). Alternatives considered but not used include time division multiplexing (TDM) and use of two subcarriers. The alternatives involved complexity (TDM of variable bit rates) and large bandwidths/intermodulation products with two subcarriers. The selected UQPSK technique uses a subcarrier frequency of 8.5 megahertz.

TABLE 2.- K_u-BAND COMMUNICATIONS MODES AND CHANNELS

(a) Forward link (ground to Orbiter, 13.775 GHz)

Mode	Modulation	Data		
1	Bi-phase-L	Ch. 1	Voice 1	32 kbps
			Voice 2	32 kbps
			Command	6.4 kbps
			Sync	1.6 kbps
				72 kbps
		Ch. 2	Text/graphics	128 kbps
			Sync	16 kbps
				144 kbps
2	Bi-phase-L		Voice 1	32 kbps
			Voice 2	32 kbps
			Command	6.4 kbps
			Sync	1.6 kbps
				72 kbps

(b) Return link (Orbiter to TDRS, 15.0034 GHz)

Mode	Modulation	Data		
1	Unbalanced QPSK	Ch. 1	Voice 1	32 kbps
			Voice 2	32 kbps
			TLM	128 kbps
				192 kbps
		Ch. 2	One of the following: A. P/L digital data, 16 kbps to 2 Mbps B. P/L recorder playback, 25.5 kbps to 1024 kbps C. OPS recorder playback, 60 kbps to 1024 kbps D. Detached payload bent-pipe data, 16 kbps to 2 Mbps	
		Ch. 3	Attached P/L digital data (realtime or playback, 2 Mbps to 50 Mbps)	
2	High modulation index FM	Ch. 1	- Same as mode 1	
		Ch. 2	- Same as mode 1	
		Ch. 3	- One of the following: A. Television composite video, dc to 4.5 MHz B. Attached P/L analog data, dc to 4.5 MHz C. Detached P/L bent-pipe analog data, dc to 4.5 MHz	

Mode 1 includes the high bit rate payload data. For this mode, it was desirable to use the same UQPSK-modulated subcarrier for the operational data and the low-rate payload data or digital recorder data. An innovative signal design was developed (ref. 13) to combine the high-rate payload data with the UQPSK-modulated subcarrier. The phase-multiplexing technique used is applicable to five channels or less and is a hybrid approach which has some of the features of both quadrature modulation and the interplex approach (ref. 14) used for deep-space communication.

An additional signal design consideration for the high-rate data in Mode 1 was signal power required to transmit 50 Mbps from the Orbiter through the TDRS. Error-correction coding was investigated, but convolutional coding was chosen because the decoding algorithms (sequential and Viterbi) provide significant coding gains at the required bit-error probability of 10^{-5} and could be implemented at 50 Mbps with moderate hardware (ref. 15). As a result of evaluating the convolutional decoding approaches, five multiplexed 10-Mbps Viterbi decoders were chosen. This approach provided the best possible performance (5.1 decibels coding gain at probability of bit error of 10^{-5}) without severe penalties in cost, complexity, and reliability. In addition, the system degrades gracefully (a coding gain of 2.7 decibels is available at a probability of error of 10^{-5}), the Orbiter encoder was simple to implement, and ground-based decoders were available and could be combined in a straightforward manner. It appears reasonable to extend the parallel 10-Mbps Viterbi decoder concept to systems requiring operation at data rates well in excess of 100 Mbps, although reliability becomes a concern as the number of parallel decoders becomes large. In fact, this parallel approach was expanded and adopted as the TDRS System (TDRSS) standard.

COMMUNICATIONS PERFORMANCE

Various tests of the K_u-band communications function have been conducted by the contractors at JSC and at the NASA John F. Kennedy Space Center. A sample test result, obtained at the JSC Electronic Systems Test Laboratory (refs. 16 and 17), is shown in figure 5.

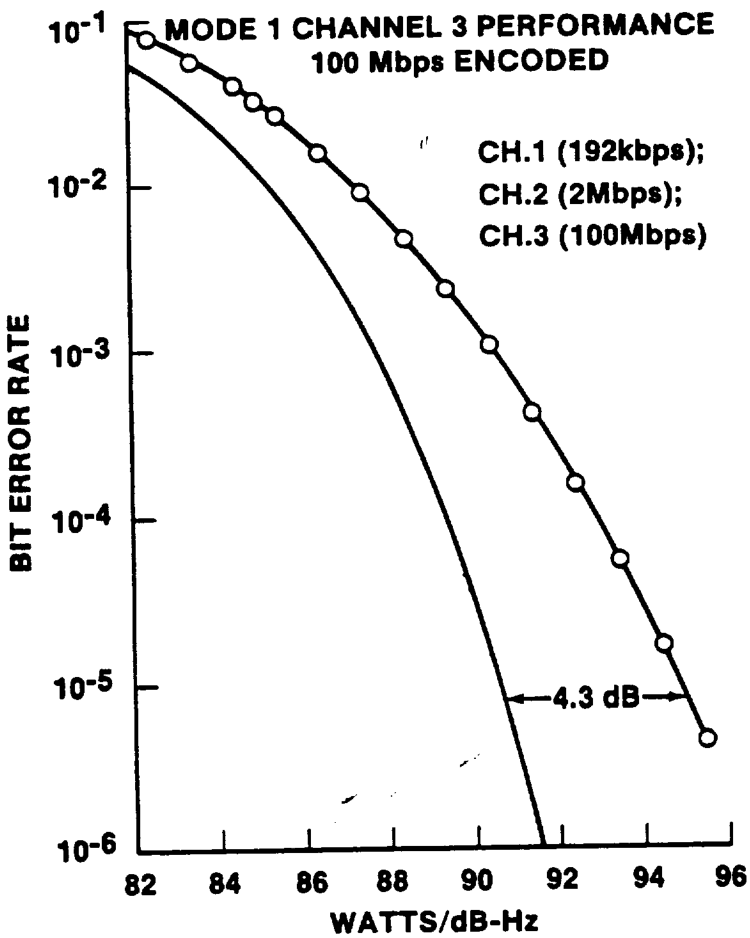

FIGURE 5.- SAMPLE K_u-BAND COMMUNICATIONS TEST RESULTS.

The first flight use of the K_u-band system was on STS-7 in June 1983. Communications performance was not tested because the TDRS was not in position. It is expected that the communications functions will be checked out on STS-8.

CONCLUSIONS

Even though complete and detailed flight performance of the K_u-band system remains to be demonstrated, some concluding remarks can be made. Development of a combined radar and communications system is feasible under the proper conditions. Weight, volume, and antenna locations can be reduced when the functions are combined. In such a case, however, both functions cannot be performed at the same time. One disadvantage of combining is that development and test activities for the two functions are interdependent. Thus, a design change or a problem in one of the functions may affect the other function and slow its progress. The more complex the system, the more likely it is that difficulties will be encountered. Also, testing of a more complex system is more challenging and requires more time because the functions cannot be tested in parallel unless more test units are built. Factors like these should all be considered and weighed in implementing future radar and communications requirements.

The development of the K_u-band system involved advances in both radar and communications. It is expected that the system will operate as specified. However, the system is complex, and performance anomalies may occur. Nevertheless, it is expected that the K_u-band system will, for many years, fulfill its role in the Shuttle Orbiter mission.

REFERENCES

1. Carrier, Louis M.; and Pope, Warren S.: An Overview of the Space Shuttle Orbiter Communication and Tracking System. IEEE Transactions on Communications, vol. COM-26, no. 11, Nov. 1978, pp. 1494-1506.

2. Cager, Ralph H.; LaFlame, David T.; and Parode, Lowell C.: Orbiter Ku-Band Integrated Radar and Communications Subsystem. IEEE Transactions on Communications, vol. COM-26, no. 11, Nov. 1978, pp. 1604-1619.

3. Cubley, H. Dean; and Ellis, Haynes: Antenna Development for the Space Shuttle Orbiter Vehicle. IEEE Transactions on Communications, vol. COM-26, no. 11, Nov. 1978, pp. 1713-1722.

4. Iglehart, S. C.: The Space Shuttle Ku-Band Rendezvous Radar. Proceedings 1980 National Telecommunications Conference, Houston, Tex., Nov. 30 to Dec. 4, 1980, pp. 66.1.1-66.1.5.

5. Alem, Waddah K.; and Weber, Charles L.: Performance Analysis of Pulse Doppler Digital Radars with Application to the Shuttle Ku-Band System. IEEE Transactions on Communications, vol. COM-26, no. 11, Nov. 1978, pp. 1620-1635.

6. Schwartz, John J.; and Feinberg, Eugene J.: STDN in the TDRSS and Shuttle Era. IEEE Transactions on Communications, vol. COM-26, no. 11, Nov. 1978, pp. 1506-1513.

7. Spearing, R. E.; Schwartz, J. J.; and Herr, D. W.: Shuttle Unique TDRS Communications. Paper presented at Space Shuttle Program Technical Conference, Houston, Tex., June 28-30, 1983.

8. Seyl, J. W.; Seibert, W. W..; Porter, J. A.; et al.: Shuttle S-Band Communications Technical Concepts. Paper presented at Space Shuttle Program Technical Conference, Houston, Tex., June 28-30, 1983.

9. Teasdale, W. E.: Payloads and Data Handling Accommodations. IEEE Transactions on Communications, vol. COM-26, no. 11, Nov. 1978, pp. 1557-1567.

10. Batson, Bartus H.; Teasdale, William E.; Pawlowski, James F.; and Schmidt, Oron L.: Shuttle Payload S-Band Communications System. Paper presented at Space Shuttle Program Technical Conference, Houston, Tex., June 28-30, 1983.

11. Simon, Marvin K.; Tu, Kwei; and Batson, Bartus H.: Effects of Data Asymmetry on Shuttle Ku-Band Communications Link Performance. IEEE Transactions on Communications, vol. COM-26, no. 11, Nov. 1978, pp. 1639-1651.

12. Vang, H. A.; and Schadelbauer, S.: Risetime Distortion of Shuttle Ku-Band Payload 50 Mbps Data Due to Coaxial Cable Skin Effects. Proceedings 1980 National Telecommunications Conference, Houston, Tex., Nov. 30 to Dec. 4, 1980, pp. 66.3.1-66.3.5.

13. Batson, B. H.; Huth, G. K.; and Udalov, S.: Phase Multiplexing for Three-Channel Data Transmission. Proceedings 1976 National Telecommunications Conference, Dallas, Tex., Nov. 29 to Dec. 1, 1976, pp. 21.6-1-21.6-7.

14. Butman, S.; and Timov, U.: Interplex - An Efficient PSK/PM Telemetry System. IEEE Transactions on Communications, vol. COM-20, no. 3, June 1972, pp. 415-419.

15. Batson, B. H.; and Huth, G. K.: Convolutional Coding at 50 Mbps for the Shuttle Ku-Band Return Link. Proceedings 1976 International Telemetering Conference, Los Angeles, Calif., Sept. 28-30, 1976, pp. 175-183.

16. Stoker, C. Jack; and Bromley, Linda K.: Electronic Systems Test Laboratory Testing of Shuttle Communications Systems. Paper presented at Space Shuttle Program Technical Conference, Houston, Tex., June 28-30, 1983.

17. Seyl, Jack W.; and Travis, Arthur D.: Shuttle Communication Systems Compatibility and Performance Testing. IEEE Transactions on Comm''nications, vol. COM-26, no. 11, Nov. 1978, pp. 1732-1744.