SPACE SHUTTLE COMMUNICATIONS AND TELEMETRY—AN UPDATE

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ABSTRACT

During operational space flight, the communications and telemetry subsystem of the Space Shuttle orbiter uses S-band and Ku-band links to provide, in addition to tracking, reception of digitized voice, commands, and printed or diagrammatic data at a maximum rate of 216 kilobits per second (kbps). The subsystem also provides a transmission capability for digitized voice, telemetry, television, and data at a maximum rate of 50 megabits per second (mbps). S-band links may be established directly with a ground station and both S-band and Ku-band links may be routed through NASA's tracking and data relay satellite system (TDRSS). A simultaneous capability to communicate with other satellites or spacecraft, using a variety of formats and modulation techniques on more than 850 S-band channels, is provided. Ultrahigh frequency (UHF) is used for communication with extravehicular astronauts as well as for a backup subsystem for state vector update. Audio and television subsystems serve on-board needs as well as interfacing with the radio frequency (RF) equipment.

During aerodynamic flight following entry, the S-band link can be supplemented or replaced by a UHF link that provides two-way simplex voice communication with air traffic control facilities.

INTRODUCTION

The orbiter's communication and tracking subsystem (C&TSS) is an unusual combination of complexity and simplicity, specialization and versatility, and off-the-shelf and newly developed hardware. It must interface with not only NASA's space tracking and data network (STDN), but also with NASA's TDRSS, the USAF space ground link subsystem (SGLS), other satellites, crew members performing extravehicular activities (EVA), and the Federal Aviation Agency's (FAA) air traffic control (ATC) voice communications. In addition, it must interface with the multiple on-board computers of the data processing subsystem, the orbiter displays and controls, other on-board subsystems, and payloads.

All of the orbiter's on-orbit communication links (Figure 1) may be employed simultaneously. For S-band operation, either the TDRSS or STDN can be employed, but not simultaneously. The design of the C&TSS was driven by several factors (Table I).

Table I. Design Drivers

Design Driver	Source	Impact
Cost	Objective to make Shuttle a low-cost launching system	• Compatability with existing ground facilities • Use of off-the-shelf when available • Limited new component development
Reuse	Objective to reuse orbiter up to 100 times	• Many environmentally sealed boxes • Extended environmental testing
Reliability	Requirement that two failures not endanger crew or vehicle and a single failure not force mission termination	• Almost completely redundant communication.
Flexibility	Requirement to interface with both DOD and NASA ground networks and inter face with a wide variety of payload communication systems	• Two turnaround ratios • Multiple payload data rates, formats, and operating frequencies
Flush or deployable antennas	Protruding antennas would burn off during entry	Considable difficulty in meeting performance requirements
Autonomy	Requirement to be independent of ground support (operate without radiating)	Development of Global Posi tioning Subsystem to obtain navigation data from stable ground-reference signals

Design Driver	Source	Impact
Power and weight	Objective to maximize vehicle payload capability	• More complex development trades and design effort • Three collectors Ku TWT
Long RF coax runs	Large size of orbiter	Special efforts to minimize losses and improve antenna and receiver/transmitter performance

Because of the complexity of the C&TSS, this paper is limited to an overview of capability and design. In those cases where companion papers describe subsystems (S-band, Ku-band, and antennas), details in this paper are further reduced and are listed in References 1, 2, 3, and 4.

SUBSYSTEM FUNCTIONAL DESCRIPTIONS

The C&TSS is most conveniently described in terms of subsystems or equipment groupings (Figure 2). Functional descriptions of these subsystems or equipment groupings are provided in the following paragraphs.

S-Band Subsystem

The orbiter's S-band communication subsystem was designed and manufactured by TRW and subtier contractors. It is comprised of two independent subsystems, the network subsystem and the payload communication subsystem. The network subsystem provides tracking and two-way communication via phase-modulated (PM) links directly to the ground or through the TDRSS and transmission of data directly to the ground via frequency modulation (FM) link. The payload communication subsystem, like a flying ground station, provides two-way communication with unmanned orbiting spacecraft.

Network Subsystem — The network subsystem consist of 8 line-replaceable units (LRU's). Those not shown as being redundant (Figure 3) are internally redundant. Therefore, the subsystem includes two electrically isolated strings (with the exception of the reeds and contacts in the switch assembly), the antennas, and their coaxial cables. Although some cross-strapping of functional units between strings is possible to improve the capability to withstand failures, this flexibility is limited to minimize orbiter wiring complexity and weight.

As may be seen from the block diagram, the FM and PM functions are separate, except that the switch assembly services both. Not shown are the interfacing multiplexer/demultiplexers (MDM's) that provide telemetry of configuration data, performance parameters, and transmission and reception of data to and from the data processing subsystem (DPS) computers. The network signal processors (NSP's) can route both data to be received and data to be transmitted through communication security boxes for decryption or encryption.

The subsystem provides for several modes and data rates (Figure 4) for both the forward link (ground-to-orbiter) and the return link[1] (orbiter-to-ground). Coding (Reference 5) is used in the tracking and data relay satellite (TDRS) modes to improve bit error rates (BER). The forward link receiving equipment is capable of handling data at two different rates, spread with a pseudo-random noise (PRN) code rate of 11.232 megachips per second or not spread, and transmitting on any of four frequencies. Spreading is used on the TDRS mode to reduce TDRS interference to ground-based communications by reducing the power flux density at the earth's surface. The four forward link frequencies accommodate two return link frequencies and two turnaround ratios (ratios of orbiter transmit to receive frequencies). Two return link frequencies, which operate in the 1.7 to 2.3 GHz band, are used to minimize interference to payload communications. Two turnaround ratios correspond to those used by NASA (240/221) and DOD (256/205).

Two data rates are available for the return link, accommodating, as in the forward link, one or two voice channels, and, in addition, two different telemetry rates. The lower data rate is used when link margins are required, as is the case for a large portion of the time when communicating through TDRSS. In the TDRS low data rate mode, where link margins are on the order of +2 to +3 dB, the power amplifier generates over 100 watts with an effective isotropic radiated power (EIRP) of 17.7 dBW and the preamplifier provides a sensitivity of approximately -125 dBm at the antenna. The antenna gain-to-noise (G/T) value is approximately -27.3 dB°K with the dual beam antennas. In direct-to-ground communication, although the power amplifier and preamplifier are not used, a transponder output of 2 watts and sensitivity of -118 dBm provide much better link margins because of the reduced range and improved (as compared to TDRS) ground terminal performance.

FM Subsystem (Operational) — The FM subsystem consists of three LRU's (Figure 3). The FM signal processor and FM transmitters provide a capability for the transmission of data not amenable for incorporation into the limited-rate pulse code modification (PCM) telemetry data stream. The data to be transmitted via FM include television, digital data from the main engines during launch, wideband (to 4 MHz) payload data, and digital data from recorder playback of payloads.

[1] The terms, forward and return links, were adopted in preference to up and down to avoid the confusion resulting from the usage of a relay satellite at a synchronous altitude where signals in both directions follow paths going both up and down.

Conditioning and multiplexing for FM transmission occur in the FM signal processor. Video and wideband digital and analog signals are routed to the FM transmitter with only matching and filtering. Narrower-band digital engine data are placed on subcarriers at 576, 768, and 1024 kHz.

The FM transmitter operates at 2250 MHz with an output power of 10 watts. Both baseband and RF filtering is provided to reduce out-of-channel interference to the PM and payload receivers. Nominal RF bandwidth is 10 MHz.

Audio Distribution Subsystem

The audio distribution subsystem (ADS), designed and manufactured for the orbiter by Telephonics, provides intercom and radio access functions for the various crew stations and hardline subscribers involved in an orbital mission. It includes facilities for audio processing, mixing, amplification, volume control, isolation, switching, and distribution. It provides paging capability, communication over various alternative audio bus circuits, distribution of caution and warning signals, and communication with ground crews during preflight vehicle checkout.

The ADS is comprised of six audio terminal units (ATU's), two speaker-microphone units (SMU's), one redundant audio central control unit (ACCU), and various interface units; their selection depends on the kind of headset being utilized.

These LRU's, except for the interface units, and their functional relationship are shown in the ADS system block diagram (Figure 5). This block diagram also indicates the relationship of the LRU's of the ADS with the radio equipment, recorders, navigation aids (NAVAID's), and hardline installations that the system serves. Two additional ATU's, one on the mid deck and one at the flight deck orbit station, are provided on Orbiter 102. These are to be eliminated as a weight-saving measure on later vehicles.

The ADS utilizes hardwire baseband transmission of audio signals and time division multiplexed transmission of control signals. The audio central control unit (ACCU) acts as a central switchboard for the system; all audio routing is accomplished in the ACCU under control of switching commands originating at the ATU's. The ATU switching commands are transmitted to ACCU in the form of serial digital data streams. The switching commands arrive independently over dedicated wires, one pair from each ATU. These control signals include channel selections, independent volume levels for each channel, and keying signals.

The mission requirements for ADS involve not only high reliability but also high speech intelligibility. The ADS audio circuits are designed to process and condition voice audio signals over a large dynamic range with minimum distortion and minimum introduction of internal noise. In meeting these requirements, close attention was given to possible sources of degradation of the voice signal as well as to all points where the signal-to-noise ratio can be safeguarded. The specific techniques employed include:

- Bandwidth filtering to the range of 300 to 3000 Hertz with 18 dB/octave slopes (minimum) at each end of the pass band.

- Usage of digital control data rates that have no repetition frequencies in the audio pass band.

- Syllabic-type automatic gain control with symmetrical clipping (followed by appropriate filtering) to standardize signal levels against variations in talking level, variations in microphone sensitivity, and distance from speaker to microphone.

- Controlled sidetone injection and extensive use of sidetone cancellation circuits to ensure that no ring-around conditions can be set up.

The overall speech intelligibility between the orbiter crew and the ground stations is above 96 percent when measured on the Harvard 1000 word test. With a weak radio link margin, and the total communication and telemetry system operating at a BER approaching 10^{-2}, the intelligibility is in excess of 80 percent.

Television Subsystem

The television subsystem allows visual monitoring from the ground of on-board activities. It provides the crew with the ability to see areas of the payload bay obscured from direct observation. Television signals originating in the orbiter, near the orbiter, and its payloads can be transmitted to the ground on either of two links, and the FM direct S-band link, or, when it becomes available, the Ku-band TDRS link.

The operational television subsystem (Figure 6), designed and manufactured by RCA, will have up to nine on-board cameras, two large-screen monitors, two portable viewfinder monitors, and the associated switching and control logic.

All TV cameras are black and white, but may be converted to color with the substitution of a color lens assembly (CLA) for the normal monochrome lens assembly (MLA). This CLA contains a rotating color separation wheel to provide a field sequential color signal. Only the two cameras located inside the cabin are to be equipped for color. One of these same cameras may be carried by an EVA astronaut outside the crew compartment. These cabin cameras are the only cameras equipped with viewfinder monitors; the pointing of all other cameras being either fixed or remotely controlled from the console television monitors (CTM).

Up to three cameras may be located in the payload bay: one at the forward end, one at the aft end, and one (keel camera) at one of four locations on the floor.

The remaining four cameras may be located on the two arms of the remote manipulating system (RMS). These two jointed-arms are to be utilized in deploying and retrieving payloads. Cameras are provided at two locations on each arm: one at the elbow and one at the wrist. The elbow camera is mounted on a remotely controlled pan-tilt unit to adjust its pointing as desired. This same pan-tilt unit is provided for the forward and aft payload bay cameras. The camera at the wrist is fixed-mounted, but has a viewing light atop it for aid in viewing shadowed areas.

The two black and white CTM's are located at the aft-end of the flight deck near the television control panel. Each has the capability for split-screen viewing, thus allowing monitoring of up to four cameras simultaneously.

These cameras and monitors are interconnected through a video switching unit (VSU), which performs switching in response to signals from the remote control logic unit (RCU). Commands are decoded by the RCU and multiplexed on the sync signal along with a camera ID. The camera's electronics decode these signals and drive the lens and pan/tilt motors. The camera multiplexes its ID number, temperature, pan/tilt angles, and angle rates on the composite video to the VSU.

In addition to its switching function, the VSU multiplexes Greenwich Mean Time from the orbiter's master timing unit on the downlink or record video and encodes one of two audio channels on the video sync signal.

Whereas the orbiter-supplied cameras produce a field sequential color signal, the TV subsystem is designed to allow a camera that generates a National Television Systems Committee (NTSC) color signal to be used. The signal format of the composite field-sequential color video is in compliance with commercial broadcast standards and would produce a black and white picture on a home television receiver.

Ku-Band Radar/Communication Subsystem

The Ku-band subsystem, currently scheduled for installation later in the flight development program, is designed and manufactured by Hughes. It operates as a radar during space rendezvous to measure angles, angle rates, range, and range rate. When not employed in this manner, it can be used as a two-way communication subsystem. It transmits data through the TDRSS at a rate of up to 50 mbps and receiving at a rate of up to 216 kbps. In both radar and communication modes, it uses a three-foot (0.9 meter) parabolic monopulse antenna that is mounted inside the front of the orbiter's payload bay and deployed by rotation about a single axis after the orbiter is in space and its payload bay doors are opened.

The deployed assembly (DA), which includes the antenna and considerable electronics, is mounted on the starboard side of the vehicle. The location of the hardware and radar range, communication modes, and maximum data rates are presented in Figure 7.

In both radar and communication modes, acquisition of the radar target or the communication satellite is aided by the onboard computer's designation of an angle around which a spiral search is conducted. Acquisition, thereafter, is automatic. Manual entry of antenna angles is also possible.

Hardware common to both radar and communications functions includes the antennas (the three-foot dish plus a small acquisition horn), the antenna drive mechanism, drive electronics, traveling wave tube (TWT) transmitter, and receiver front end.

Hardware is packaged in four LRU's (Figure 8). All hardware, except the communications signal processor, are used for radar. All hardware except electronic assembly 2 (EA-2), are used for communications.

All externally generated control signals are applied to electronic assembly 1 (EA-1) and distributed with internally generated control signals to the other LRU's. Control of radar functions is accomplished by feeding signals directly from display and control (D&C), but communication control signals originating at the D&C are routed through the ground control interface logic (GCIL), to permit communications functions to also be controlled from the ground.

Because failure of the communications function becomes self-evident rather quickly, provision is provided to automatically switch to the S-band network subsystem.

Table II provides some Ku-band subsystem parameters applicable to both radar and communications.

The parabolic antenna has two uncommon features. It is edge mounted with supports radiating from its mounting point and is constructed largely of graphite-epoxy to minimize thermal distortion. In angle tracking modes, antenna sum and angular error signals are processed. The elevation and azimuth signals are time-multiplexed, eliminating the need for a third processing channel.

Table II. Ku-Band Subsystem Parameters

Narrow Beam Antenna	Prime feed parabolic
Type	38.4 - 38.9 dB*
Peak gain	1.57 -1.680'°
3 dB beamwidth	RHCP/linear
Polarization	
	Horn
Wide Beam Antenna	18 dB
Type	20°
Gain	Linear
Beamwidth	
Polarization	50 W
	5 dB max.
Common Parameters	28 vdc
TWT output	
Receiver NF	
Prime power	
*Frequency dependent	

Although concern had been originally expressed over the wisdom of combining a communications and radar system, it is now obvious that savings in weight, volume, and developmental costs were attained without significantly degrading either function.

Radar Function — As a rendezvous aid, the Ku-band subsystem operates as a pulse doppler, frequency-hopping radar. The relatively long 66-microsecond pulses employed at longer ranges provide reasonable efficiency with the peak-power-limited TWT amplifier. Short pulses of 22 nanoseconds are used to provide radar operation down to 100 feet (30 meters). Pulse widths and repetition frequencies are selected to provide unambiguous measurement of both range and range rate for uncooperative (skin-tracked) targets to 10 nmi (18.5 km).

Because the orbiter in space performs the latter part of rendezvous and station-keeping by accelerating and braking along the z axis (the axis that runs vertically through the orbiter), the radar normally searches angles within 30 degrees of a straight upward pointing position. Tracking, however, may continue through larger angles until the beam is intercepted by the orbiter structure.

Radar accuracy characteristics are summarized in Table III. The velocity accuracy requirement led to the choice of a pulse doppler approach. Sixteen doppler filters cover the doppler interval defined by the repetition rate.

Table III. Radar Passive Target Requirements

Range accuracy (3σ)	80 feet or 1 percent
Velocity accuracy (3σ)	1 ft/s
Angle accuracy (3σ)	8 milliradians
Angle rate accuracy (3σ)	0.14 milliradians/sec

Like the S-band payload communication subsystem, the radar must operate over a large dynamic range. In addition to concern over receiver dynamic capability, nearby targets could be damaged by excessive energy from the radar. In order to prevent damage, the three levels of output power provided are 50 watts full power with -12 and -24 dB steps of attenuation.

An auxiliary (acquisition) antenna provides a convenient source for a guard signal, which is processed and compared to the narrow-beam sum signal to eliminate sidelobe targets. Because the auxiliary antenna gain is 20 dB less than the gain of the main antenna and because antenna sidelobes are down 20 dB or more, there is at least a 20-dB difference in the main/ guard ratio for mainlobe and sidelobe targets.

Communication Function — Ku-band subsystem communications provide the orbiter with a highly flexible means of transmitting data at various rates and formats (Table IV). Except for the 192-kbps channel, which is comprised of the orbiter voice and telemetry (operations data), other rates and bandwidths shown are maximums. From the rate ranges shown, it may be seen that the capability extends continuously from 16 kbps to 50 mbps. Similarly, the 4.5 MHz analog channel extends downward to dc. The unusual signal design provides quadraphase shift keying (QPSK) of a subcarrier and either QPSK or FM of the carrier.

Table IV. Return Link Data Rates

Mode	Channel	Data Rate	Modulation	
1 (Digital)	1	192 kbps	QPSK of 8.5 MHz subcarrier	QPSK of carrier
	2	16 kbps - 2 mbps		
	3	2 - 50 mbps		
2 (Digital/ Analog)	1	192 kbps	QPSK of 8.5 MHz subcarrier	Summed; high MI FM of carrier
	2	16 kbps - 2 mbps		
	3	0 - 4 MHz analog		

The problem of mutual acquisition of the orbiter and TDRS has received considerable attention. In one acquisition scenario, the orbiter radiates Ku-band energy at the TDRS through the widebeam acquisition antenna. The TDRS locates this signal and points its narrow (0.36-degree) beam at the orbiter, which searches and acquires with the narrow beam antenna, and then, switches its transmitter to the narrow-beam antenna. In a similar scenario, the orbiter radiates S-band energy through the appropriate antenna and the TDRS points its S/Ku-band antenna at the S-band source. It even appears possible that available orbital parameters will be good enough to allow both TDRS and orbiter narrow-beam antennas to be pointed at each other with sufficient accuracy to achieve acquisition without search.

Failure of the forward link results in a signal being generated in the signal processor, which commands the GCIL to switch the NSP forward link input from the Ku-band to the S-band receiver. This precludes the possibility of the ground losing communication with the vehicle should a Ku-band forward link problem develop while the crew is asleep.

As in the S-band subsystem, spreading of the forward link is used to reduce interference to ground-based communications systems. The PRN code rate is 3.02803 megasymbols per second, less than that used at S-band.

Ground Command Interface Logic (GCIL)

GCIL is an LRU that provides the capability for ground control of many functions of C&TSS and a portion of the operational instrumentation subsystem. It also provides the logic to allow control of the same functions from either D&C switches (manual commands) or in response to ground-originated commands through either the S-band or Ku-band links. Ground-originated commands flow through the NSP to the general-purpose computers (GPC's) of the DPS. Commands are sent to the LRU's. Then, the command status (from either the GCIL or the LRU's) is returned to the GPC and routed to the ground through the pulse code modulation (PCM) data stream. The GCIL provides logic to allow the on-board crew, if required, to block ground-originated configuration commands.

On-board commands may also be originated through the usage of any of several DPS keyboards that enter the command directly in the GPC.[2]

The GCIL, in conjunction with the other described equipment, allows a ground crew to operate and monitor the C&TSS configuration, freeing the crew for other activities. It also avoids the necessity of having one astronaut awake at all times just to maintain contact with the ground.

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[2] The term, GPC, includes all five of the operations (OPS) computers on board, including those previously referred to as guidance, navigation and control (GN&C) computers.

UHF

UHF transceivers are provided for the transmission and reception of voice to allow contact with ATC facilities and chase aircraft during landing operation. They are provided during on-orbit operations for the transmission of voice to and the reception of voice and telemetry from extravehicular space-suited astronauts. Both functions are provided by a newly developed EVA-ATC communication subsystem being built by RCA under direct contract to NASA.

EVA/ATC Communication System — The EVA/ATC communication subsystem is designed primarily to support extravehicular activities, but it also provides ATC voice communication capabilities. Thus, allowing it to replace the ARC-150 already used on Orbiter 101. In the ATC service, it provides two-way RF links on either of two frequencies (296.8 or 259.7 MHz) with a transmit power of 10 watts. In addition, emergency communication is provided by a 243-MHz guard channel transmitter and receiver.

In EVA service, things are more complicated. To understand the various modes of operation, it is necessary to consider the extravehicular communicator (EVC) equipment carried by the EVA astronaut or astronauts. Basic block diagrams of both the orbiter's EVA/ATC transceiver and the EVC are presented in Figure 9.

The EVA unit consists of AM transmitters, AM receivers, a telemetry subsystem, a warning subsystem, and an antenna. This equipment is arranged to operate in several different modes. Mode A is the normal mode used by a single EVA astronaut and Mode B is the normal mode by a second EVA astronaut (Figure 9). Other combinations of receivers and transmitters can provide voice communication if there is equipment failure or interference on normal channels.

In the RF OFF mode, the equipment provides duplex voice operation utilizing an audio input/ output interface to the Shuttle orbiter via a service umbilical.

In Modes A and B, the operating transmitter is modulated by a 5.4-kHz (standard IRIG) subcarrier oscillator, which transmits biomedical data (electrocardiographs). Voice, which modulates the carrier directly, is keyed on by voice-operated circuitry (VOX) or a push-to-talk (PTT) switch.

A 1.5-kHz warning tone generator, square wave modulated at 15 Hertz, operates in response to a sensor (external to the EVC) to alert the astronaut to conditions requiring his attention.

On the orbiter side of this communication link, receivers and 500-milliwatt transmitters are provided on each of the frequencies shown in Figure 10. Two antennas are provided: one inside the airlock and one on the bottom of the orbiter. The latter is the same one used with the ARC-150 during aerodynamic flight tests.

The processing within this system strips the electrocardiograph signals from one or two EVC's and provides them to the orbiter telemetry subsystem. A two-way voice interface with the orbiter's audio distribution subsystem is provided, giving astronauts performing extravehicular activities access to orbiter voice communications on up to three voice channels. This enables an EVA astronaut to be in direct voice contact with the ground or the orbiter crew. The astronaut can also have his conversations recorded.

S-Band Payload Subsystem

The S-band payload subsystem provides the capability to communicate with a wide variety of satellites. It will be used for such purposes as checking the operation of an attached on-board or a released payload prior to moving from its immediate vicinity in the orbiter payload bay. Also, it can help with the safing of a satellite before taking it on-board for repair or return to earth. Two separate payload subsystems are available. First, a subsystem to operate with STDN or DSN, and second, a subsystem to operate with the space ground link subsystem (SGLS) network.

The subsystem provides for several modes and data rates in addition to multiple frequency selection for transmit and receive (Figure 11). The receiver and transmitter are packaged in a single LRU called the payload interrogator (PI), which is used for both NASA and DOD. Signal processing in both directions is performed in either the payload signal processor (PSP) for NASA payloads or the communication interface unit (CIU) for DOD operations. Redundant LRU's are carried for both the PI and PSP, while the CIU is a single unit (Figure 12).

The PI provides 851 duplex channels for simultaneous reception and transmission of information with a coherent frequency of 256/205 in the DOD mode (20 channels) and 240/221 in the STDN (808 channels) and DSN (23 channels) modes. In addition, provision for six receive-only RF channels and four transmit-only RF channels in the DSN mode (Figure 13) are included.

Because payloads are intended to communicate with the same ground stations as the orbiter, they also receive on the lower frequencies of the space communication band and transmit on the high frequencies of the same band. This means that the interrogator must receive on frequencies near those employed for transmission by the S-band network subsystem. Transmission frequencies are close to those where the network subsystem receives data. Careful filtering is employed in both subsystems to minimize cross interference. The upper and lower frequency region is selected in the network subsystem to maximize separation from the payload channel in use (Figures 11 and 4).

Both the receiver and transmitter of the PI are capable of performing sweep for acquisition and automatically terminating the sweep upon acquisition. The receive sweep is selectable for a plus-or-minus 80 to 140 kHz range for signal acquisition within 5 seconds. The transmitter sweep is 540 Hz/s in the DSM or DOD mode for a sweep range of plus-or-minus 33 kHz. Also in the DOD mode the sweep rate is 10 kHz/s for a sweep range of plus-or-minus 55 kHz. In the NASA mode, the sweep rate is 10 kHz/s for a sweep range of plus-or-minus 75 kHz.

The receiver section of the PI is equipped to demodulate the subcarrier for data processing by the PSP or CIU, or transfer via the Ku-band through the TDRSS to the ground.

The standard received signals are:

a) $\beta = 1 \pm 0.1$ radian, SCO = 1.024 MHz, Data 1, or 2, or 4, or 8, or 16 kbps (Biϕ or NRZ)
b) $\beta = 1 \pm 0.1$ radian, SCO = 1.7 MHz, data $\leq$ 256 kbps (PSK), or FM/FM with up to $\pm$200 kHz P-P SCO deviation
c) $1.1 \geq \beta \geq .2$ radian $\begin{cases} SCO_1 = 1.7 \text{ MHz, data} \leq 256 \text{ kbps (PSK),} \\ \quad \text{or FM/FM with up to } \pm 200 \text{ kHz P-P SCO deviation} \\ SCO_2 = 1.024 \text{ MHz, data} \leq 64 \text{ kbps (PSK)} \end{cases}$

Item a) is compatible with STDN/DSN while Items a), b), c) are compatible with DOD and the Ku-band bent pipe.

The non-standard PI received signals must meet all of the following requirements to be bent pipe compatible for Ku-band transfer:

a) PM $2.5 \geq \beta 6 \geq 0.2$ radians, with a minimum residual carrier of -114 dBm for acquisition and -116 dBm for tracking
b) The inband data spectral components within ±100 kHz of the receive carrier frequency shall be 26 dB or more below the RF carrier power
c) The intelligence contained in the received signal shall be ≤ 4.5 MHz to be compatible with the one-sided 3 dB post detection bandwidth of the PI receiver

In addition to the above, the received signal, with direct carrier modulation by a nonperiodic digital information channel, is accepted provided that; the RMS phase noise component, because of modulation sidebands, is 10 degrees or less, and the maximum allowable number of transitionless bits will not contribute more than 18 degrees to the carrier phase noise.

The transmitter section of the PI is equipped to modulate the selected carrier signals generated by the PSP or CIU for transmittal to a NASA, DSN or DOD compatible satellite.

The standard transmit signals are:

a) $\beta = 1 \pm 0.1$ radian, SCO 16 kHz, commands = n x 125/16, where $n = 2^x$ and x integer 0 to 8
b) $2.5 \geq \beta \geq 0.2$ radian, SCO's: 65 kHz or 76 kHz or 95 kHz, AM: 500 Hertz or 1000 Hertz. Commands: 1 K-Baud or 2 K-Bauds

Item a) is compatible with STDN/DSN while items a) and b) are compatible with DOD.

The non-standard transmit signals are a high tone sinewave command as follows for DOD operation:

a)	Frequency range	- 1 to 200 kHz
b)	Duration	- "1" tone 0.1 to 3.5 seconds (TD)
		- "0" space 0.1 to 3.5 seconds (SD)
		Interval 0.1 to 6 seconds
c)	Type	- Sequential NRZ keying (Figure 14)

To aid in accommodating the large variation in signal strength, which results from a range that can vary from a few feet to several miles, the receive section of the PI automatically adds protective attenuation. Signals greater than -116 dBm at the orbiter payload antenna will be automatically tracked. Protection for +20 dBm signals are incorporated in the PI. Three selectable EIRP power levels are provided by the PI. These are: +29 dBm (maximum), +19 dBm, and -4 dBm.

The PSP and CIU demodulate the subcarriers, provide bit synchronization and frame synchronization. The PSP provides four frame synchronization word lengths (8, 16, 24, and 32 bits). Bit synchronization will accommodate Bi-ϕ-L, -M, -S, and NRZ-L, M, S; one at a time, for a single selected data rate of 1, 2, 4, 8, or 16 kbps.

The demodulated telemetry plus clock and frame sunchronization is routed to a payload data interleaver (PDI). The PDI, a component of the instrumentation subsystem, interleaves the telemetry data with data from up to four attached payloads for eventual transmission to the ground in the PCM data stream via the network subsystem.

The CIU handles one of eleven data rates (0.25, 0.50, 1.2, 4, 8, 10, 16, 32, 48, 64 kbps) Bi-ϕ-L on a 1.024 MHz subcarrier and a constant data rate between 0.125 and 256 kbps Bi-ϕ-L on a 1.7 MHz subcarrier. The former data rate is transmitted to the ground via the

PDI while the latter is transferred via the FM subsystem or FM phase of the Ku-band subsystem.

The PSP also receives configuration and payload command messages from the DPS at a burst rate of 1 mbps. It responds to a configuration message by configuring itself to handle data at rates and formats designated. It buffers the commands to phase shift keyed modulate a 16 kHz subcarrier for transmission by the PI or hardline to attached payloads. The CIU accepts command from the satellite control-facility (SCF) via the network subsystem and DPS or direct on-board generated command, which can override the DPS. The command is buffered, verified, and changes from Bi-ϕ-L to ternary and modulates a 1.024 MHz subcarrier for transmission by the PI to a detached payload.

Antennas — The antennas associated with each subsystem (except the UHF airlock and the deployable Ku-band) are flush mounted (Figure 15). The locations were chosen to favor the desired direction of, coverage within the constraints of the space available on-board the orbiter.

All flush antennas are overlaid with the thermal protection subsystem (TPS), which covers that part of the orbiter surface that otherwise would be unable to survive the heat of entry. TPS is thickest on the bottom to a depth over the lower antennas reaching 2.5 inches. TPS has electrical characteristics somewhat similar to polyurethane foam. It has required special attention where the patterns are critical (quads). Basic data on the antennas are presented in Table V.

Table V. Orbiter Antennas

Antenna	Quantity	Freq	Polar	Type	Reason for Selection
UHF	1	UHF	LV	Annular slot	High efficiency, broad angular coverage
S-band quads	4	S	RHCP	Crossed dipole fed cavity fixed array	Beam shaping, gain, efficiency
S-band hemi's	2	SS	RHCP	Crossed dipole fed cavity	High-efficiency, broad, continuous coverage
S-band payload	1	S	RH& LH CP	Cross dipole fed cavity	Polarization switching, shaped beam
UHF-airlock	1	UHF	L	Microstrip	Total coverage in the airlock cylinder
Ku-band subsystem	1 or 2	Ku	L radar CP comm	Parabolic	High gain, low sidelobes

The four dual beam quad antennas are placed in the roll plane of the vehicle at 45 degrees to the orbiter horizontal plane. The patterns of about 100 degrees in roll provide overlapping roll coverage; fore-aft coverage is on the order of 130 degrees. More details on orbiter antennas and patterns may be found in References 1, 3, and 4.

DISPLAYS AND CONTROLS (D&C's)

Communication control panels in the orbiter are not too different from their counterparts in large commercial aircraft and previously manned spacecraft. All panels (not just C&TSS) are designed and manufactured by the orbiter prime contractor, Rockwell International, to ensure commonality of component usage and standard layout and nomenclature.

The S-band control panel (Figure 16) makes use of block diagramming to aid in understanding switch functions; a technique that also shows on the bottom of the Ku-band control panel (Figure 17). The signal strength meter on the Ku-band panel is shared between the S-band PM (network) subsystem, the S-band payload subsystem, and the Ku-band subsystem. The striped barber poles, two-state displays, are more reliable and easier to view under various lighting conditions than pilot lights.

Additional information on the C&TSS is available on the DPS cathode-ray display. Most interesting of the data that can be called up is the antenna status display, the center of which is shown in Figure 18. This display shows the volume around the vehicle as if a tube had been placed around the fuselage, split along the bottom, and flattened. The nose is a line across the top of the figure, the tail the line across the bottom of the figure, and both sides of the figure represent the bottom fore-aft centerline of the vehicle. The oddly shaped figures are the outlines of the angles where the Ku-band beam would be blocked by the vehicle. Moving symbols E, W, and S are the directions to east and west TDRS and to the nearest ground station. Obviously, they are not all always on the display. The square around the W indicates the Ku-band antenna is pointing toward TDRS west. The pairs of letters along the top of the display indicate that the S-band quad that best serves those 90-degree quadrants (LL = lower left, LR = lower right, etc.). This center display is surrounded by other antenna status and signal strength data. The GCIL unit that operates in conjunction with D&C's has been previously discussed.

SUBSYSTEM PHYSICAL DESCRIPTION

The C&TSS utilizes both environmental sealed and unsealed LRU's, with most of those specifically designed for the orbiter being sealed as an aid toward meeting the goal of a ten-year life. A typical box is approximately 7.6 inches (19 cm) high and no longer than 20 inches (51 cm), with width being determined by the volume needed. A flat thermal base provides contact with water-cooled shelves on which or under which it mounts

(Figure 19). Hold-down is by captive fasteners. Connectors are on the front panel. The physical design was greatly influenced by the sealing requirement, conduction cooling, and by the design vibration requirement of 0.03 g^2 per Hertz.

A summary of subsystem weight and power consumption is provided in Table VI. Power dissipation is about the same as consumption except for those LRU's that generate significant amounts of RF. Power consumption is not totaled because all of the subsystems are never on at the same time. In addition to the powers listed, there are short-term switching transients as latching relays are switched and intermittent heater-power for TV cameras and the Ku-band DA, which are external to the temperature-controlled crew compartment.

Table VI. Power Consumption and Weight of Subsystems

Subsystem	Quantity of LRU's	Power Consumption* (Watts)	Weight** [lb (kg)]
UHF-ATC transceiver	1	160	18 (8)
Audio distribution	9	75	56 (25)***
Global positioning	4	240	105 (48)
S-band			
Network	13	797	218 (99)
Payload	4	121	66 (30)
Ku-band	4	Radar 429 Comm 489	271 (123)
Television (operational)	18	528****	279 (127)
Ground command interface logic	1	60	39 (18)
Antennas	22	-	76 (35)
Total	76	-	1128 (513)

Notes:
*Sum of LRU's that normally operate simultaneously
**LRU's only—excludes wiring coax, and C&D
***Excludes headsets, interface units, and cables
****All cameras on

Although weight was an important design driver, it lost when traded against several other factors. One design consideration that added weight was the 100-mission design goal, which resulted in most of the LRU's of the RF being sealed. Studies on weight reduction of communication LRU's revealed the cost was prohibitive.

Most of the LRU's of the C&TSS are mounted in equipment bays located at the fore and aft ends of the mid deck along with LRU's of other orbiter subsystems. In these bays, wires to LRU connectors are in trays in front of the equipment for easy repair and modification. Where feasible, redundant LRU's are mounted in separate bays for damage control.

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3. Hoagland, J.C., and Pope, W.S., Space Shuttle Orbiter S-Band Communication Development Problems, IEEE, International Electrical and Electronic Conference and Exposition, Toronto, Canada, September 1977.

4. Hoagland, J.C., S-Band Communication on the Space Transportation Systems Space Shuttle Orbiter, Session 21, Part II, Wescon Professional Program, Los Angeles, California, September 1978.

5. Lindsey, W.C., Synchronization System on Communication and Control, Prentice Hall, 1973.

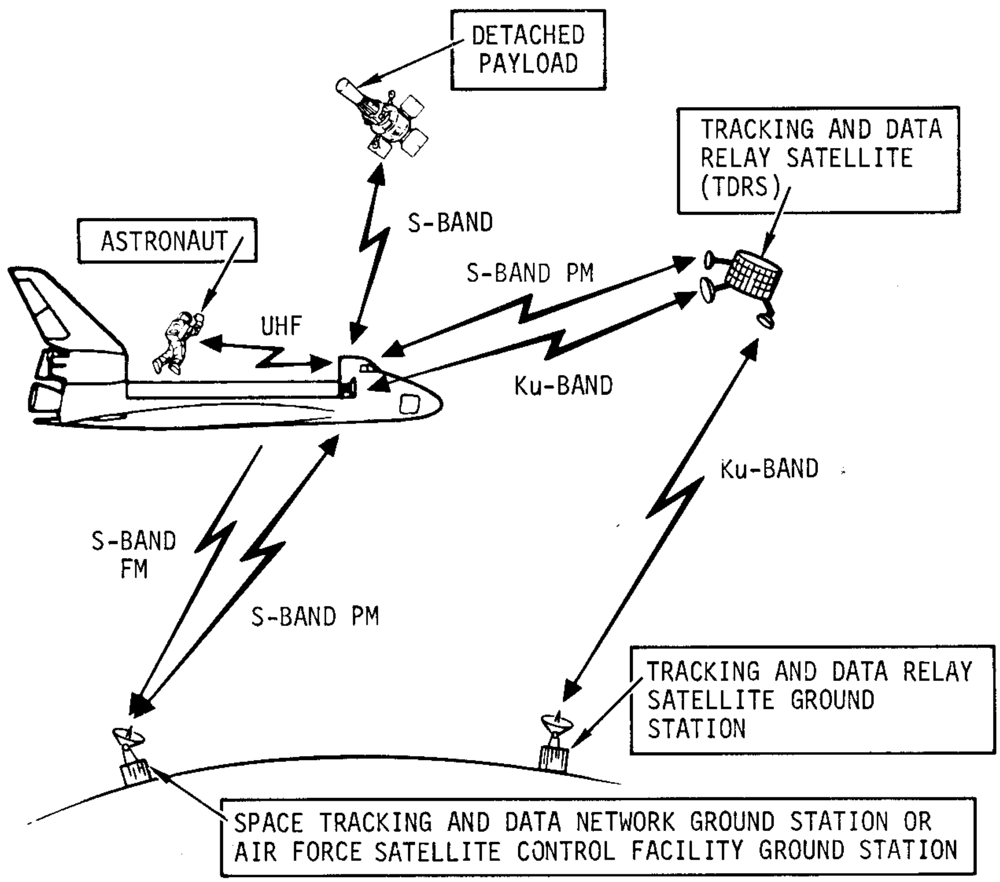
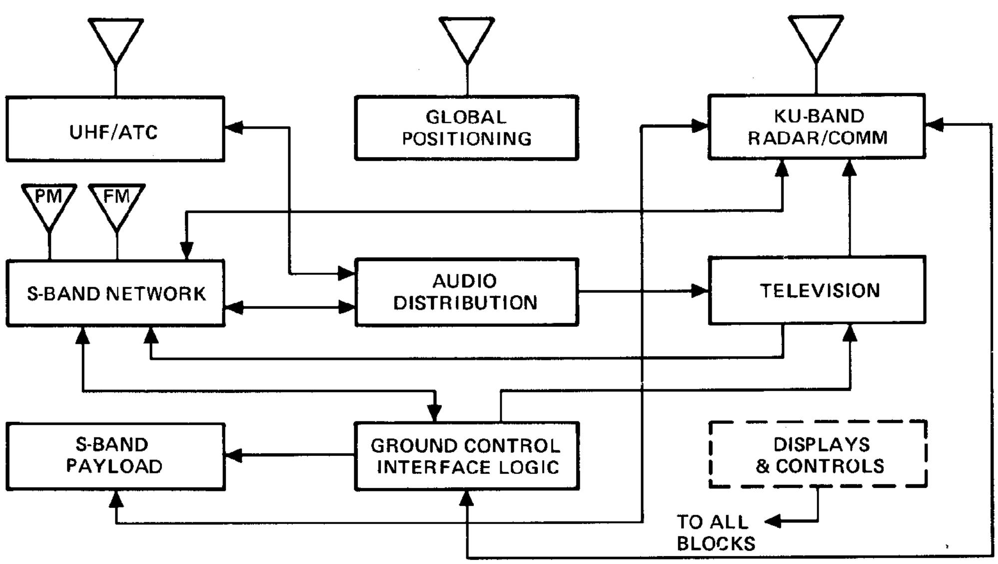


Figure 1. Orbital Communication Links



NOTE: INTERFACES WITH OTHER SUBSYSTEMS ARE NOT PRESENTED. ANTENNAS, EACH SYMBOL REPRESENTS ONE ANTENNA OR A GROUP OF THEM, ARE TOGETHER FOR CONVENIENCE; THEY BELONG WITH THE SUBSYSTEM THEY SERVE AND A SIMILAR SITUATION EXISTS FOR DISPLAYS & CONTROLS.

Figure 2. Subsystem Groupings

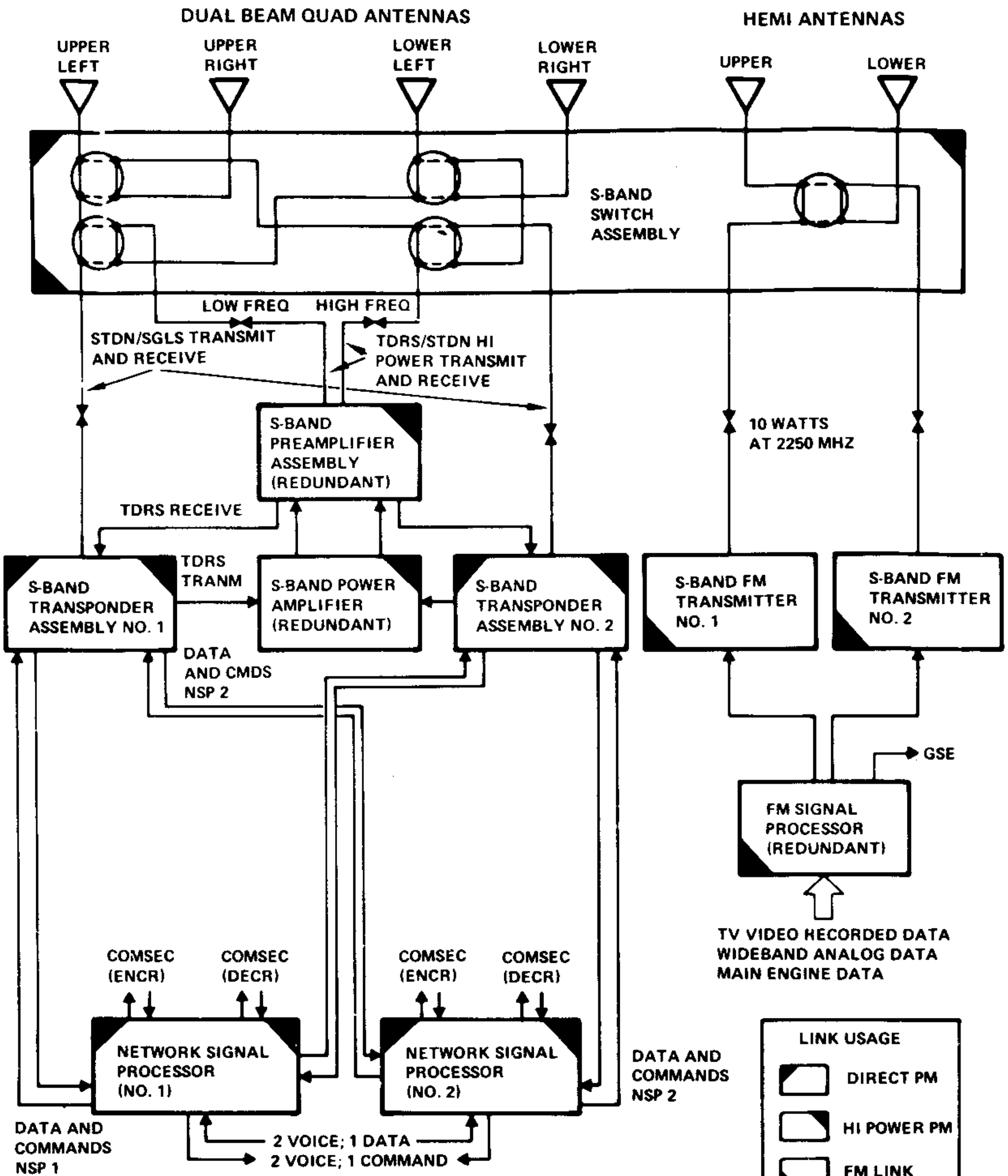


Figure 3. S-Band Subsystem Block Diagram

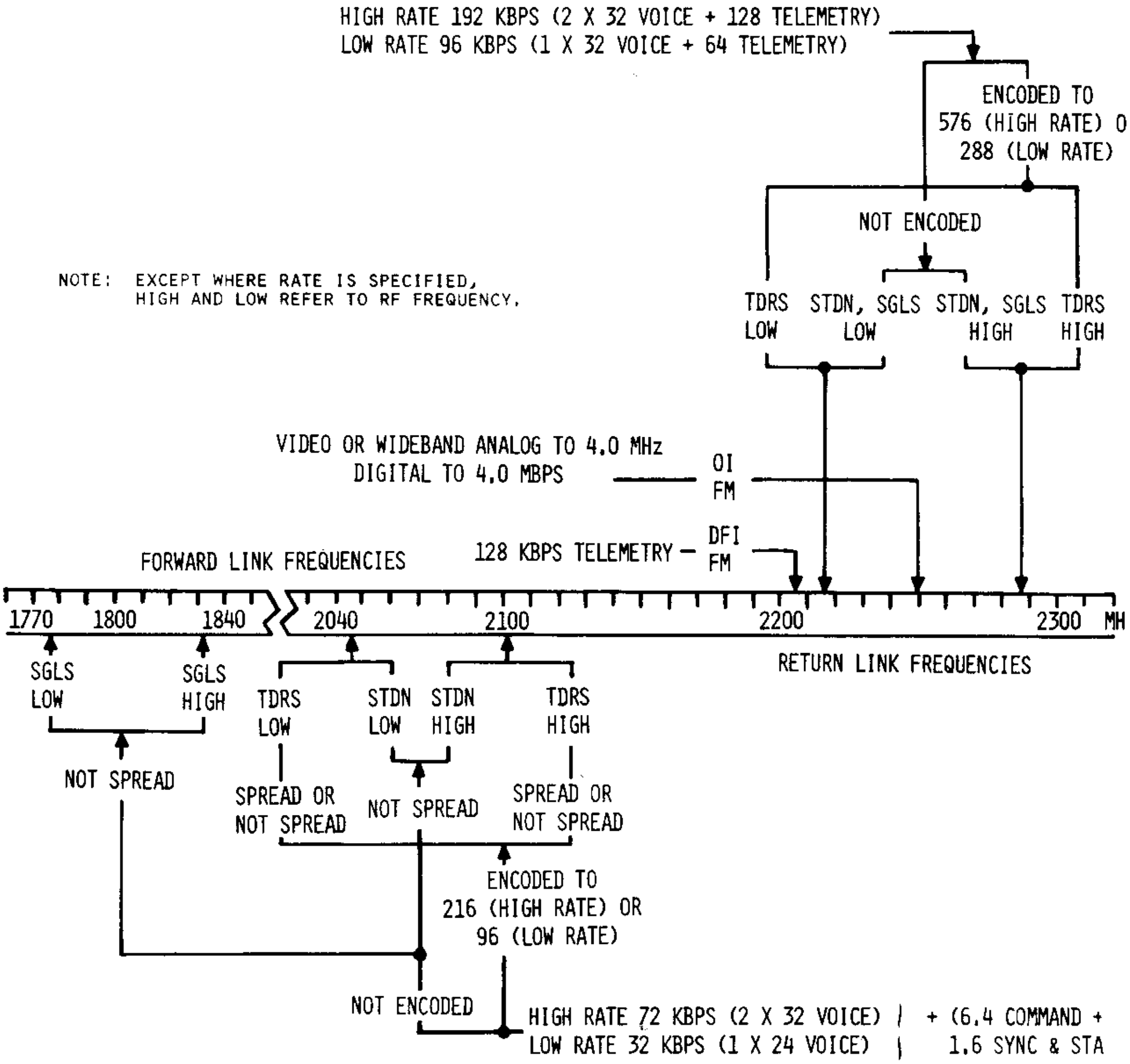


Figure 4. S-Band Frequencies, Modes, and Data Rates

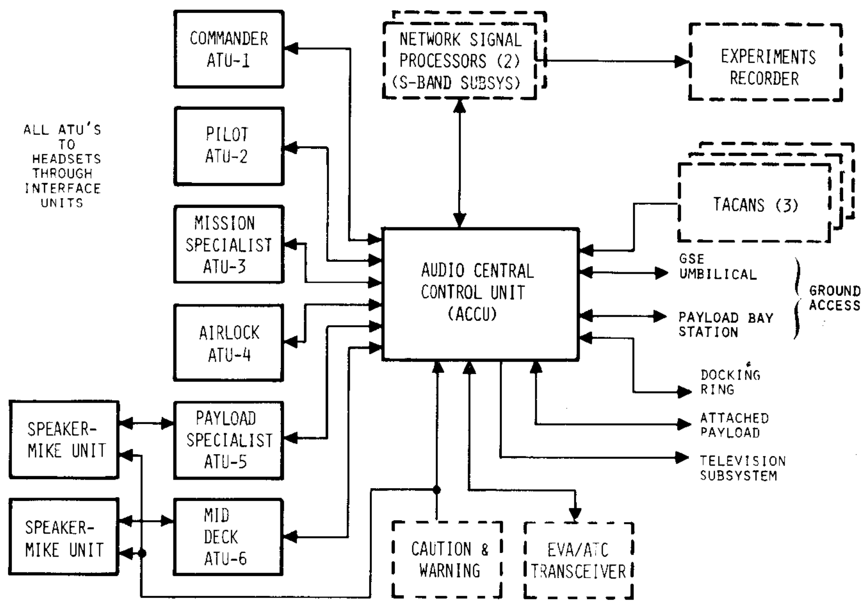


Figure 5. Audio Distribution Subsystem Block Diagram

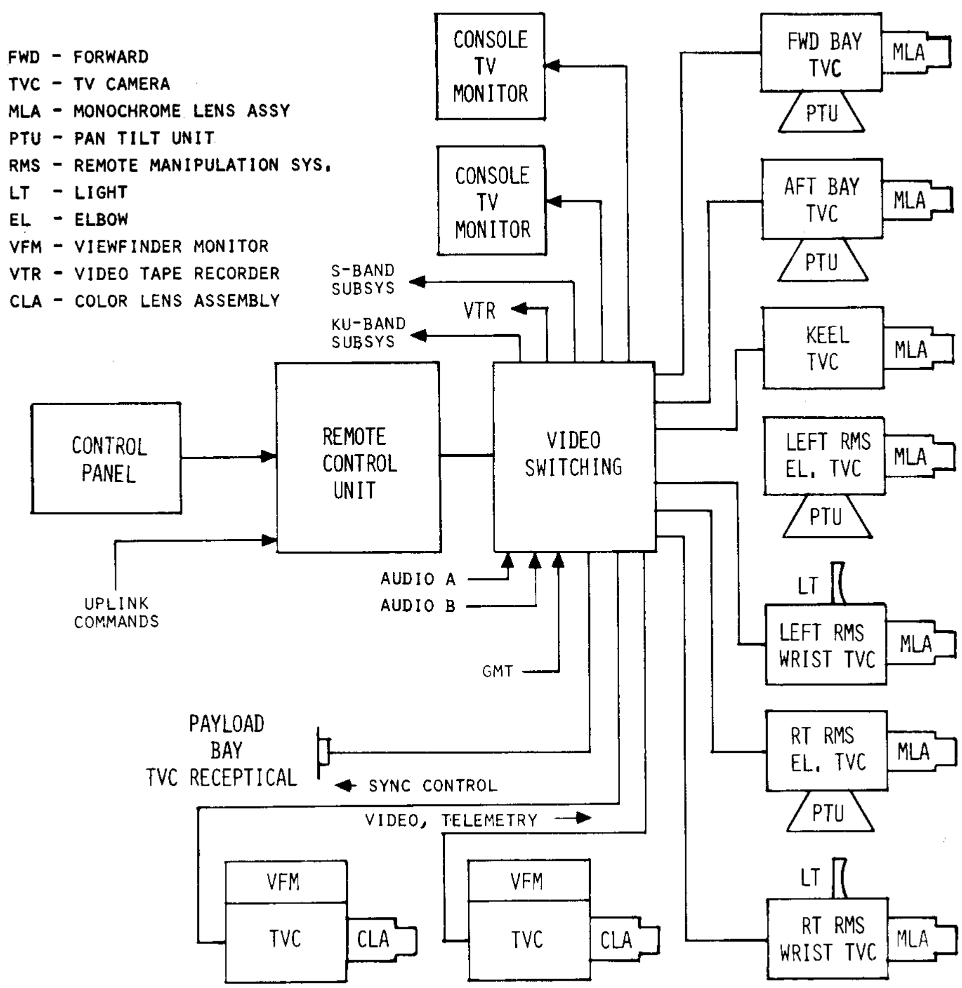


Figure 6. Operational TV Subsystem Diagram

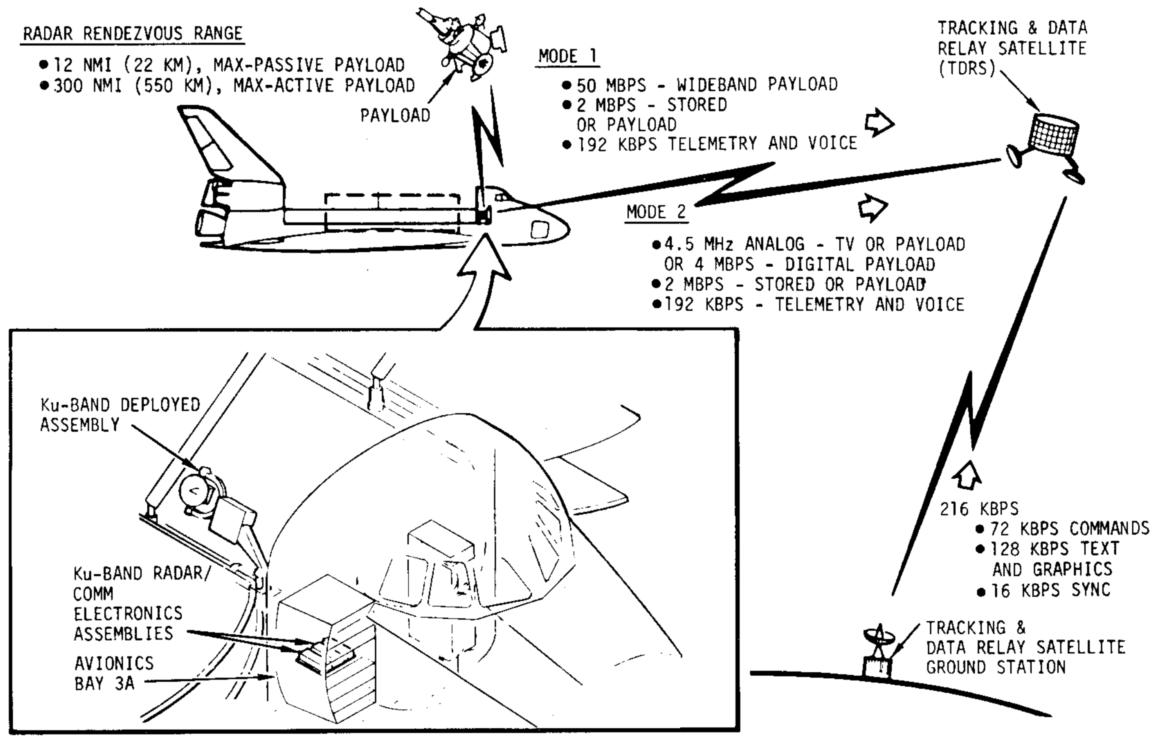


Figure 7. Ku-Band Radar/Communication Subsystem

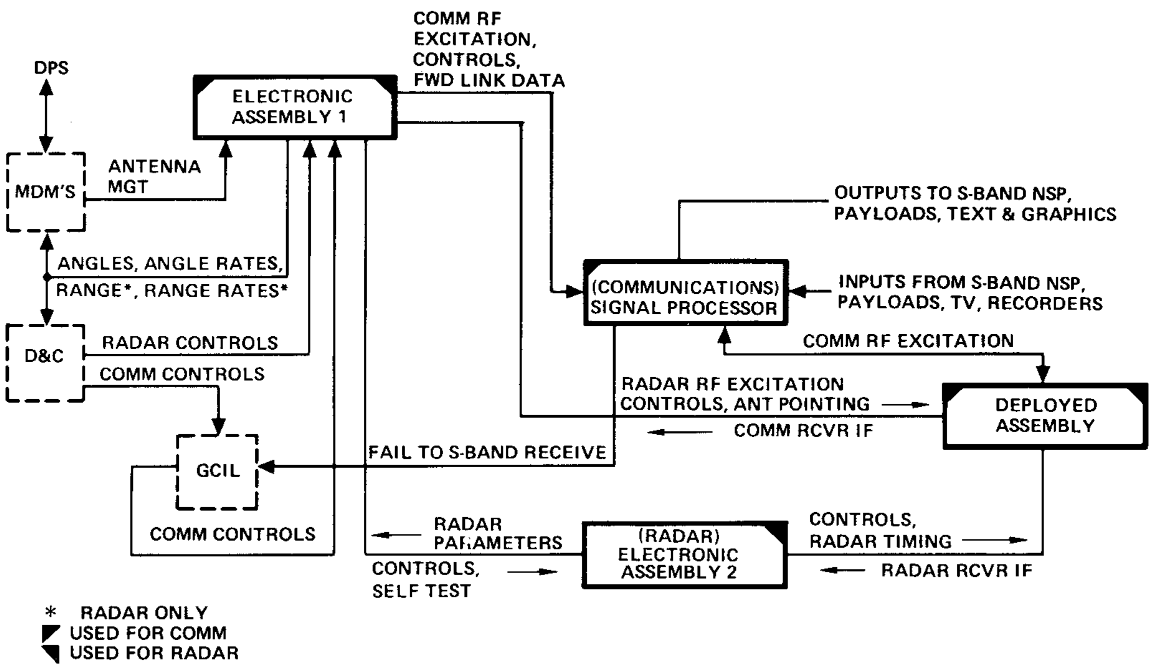


Figure 8. Ku-Band Subsystem Block Diagram

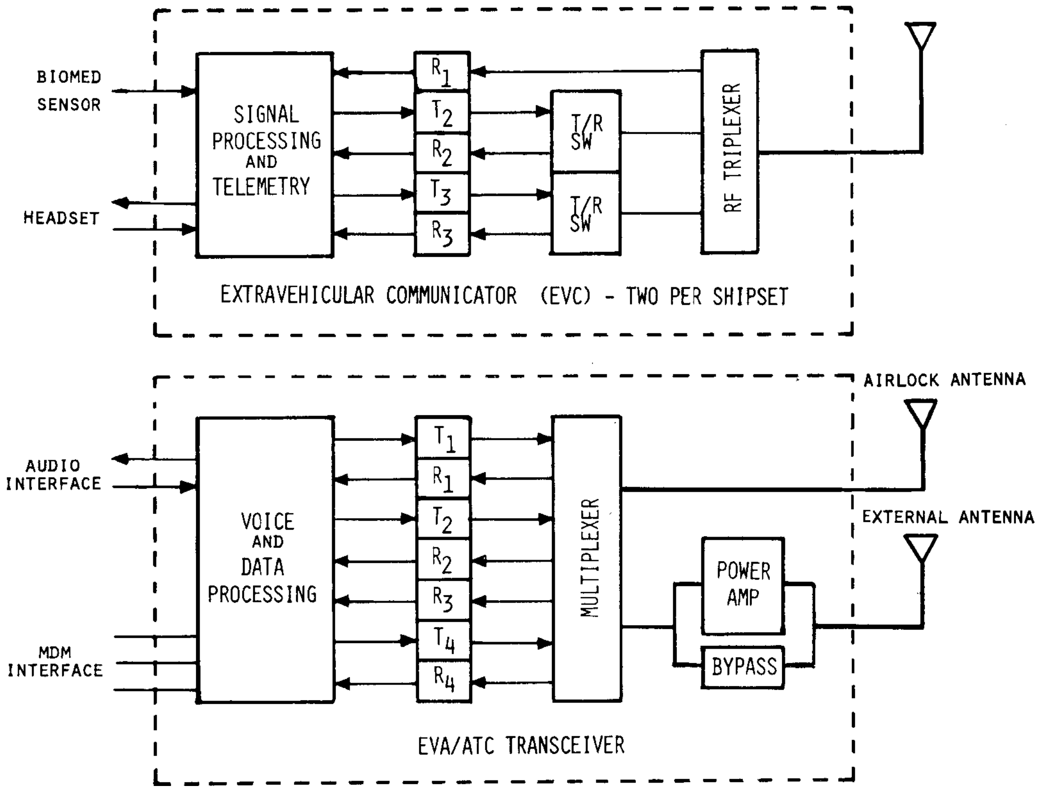


Figure 9. EVA/ATC Subsystem Block Diagram

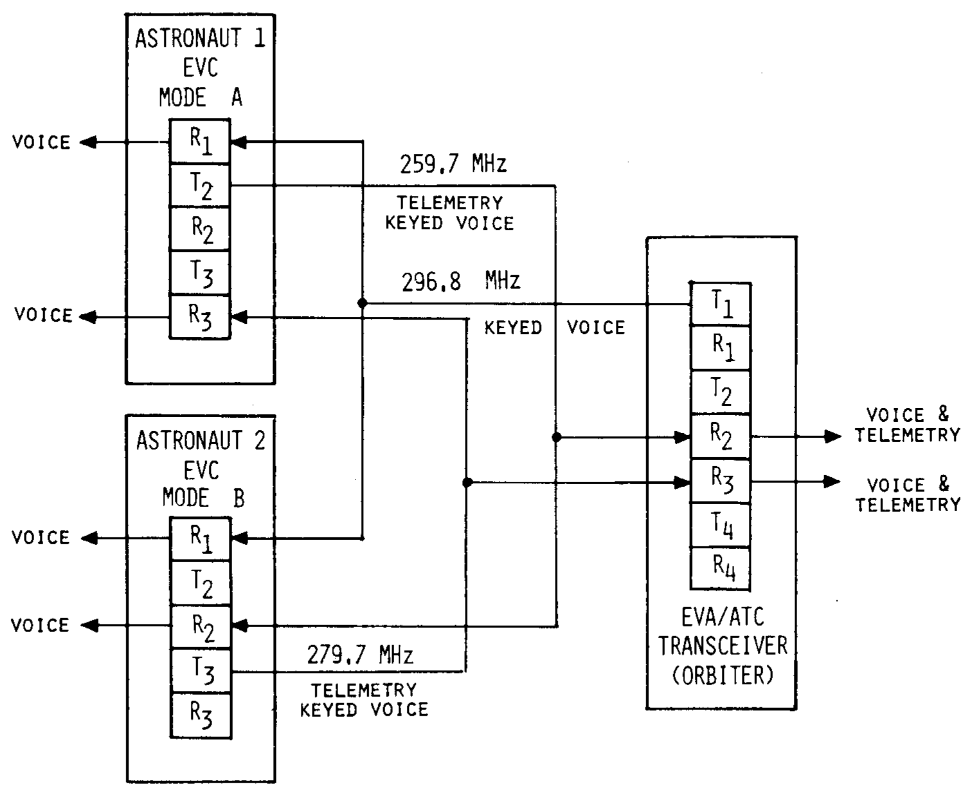


Figure 10. EVA Communication

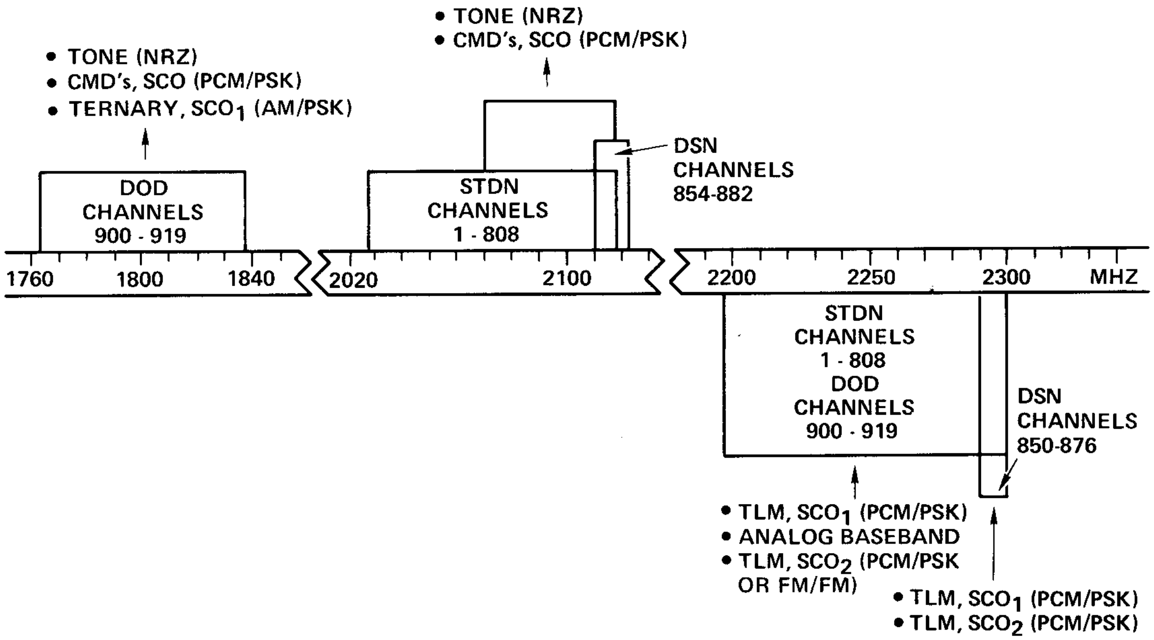


Figure 11. Payload Frequencies, Modes, and Selected Data Rates

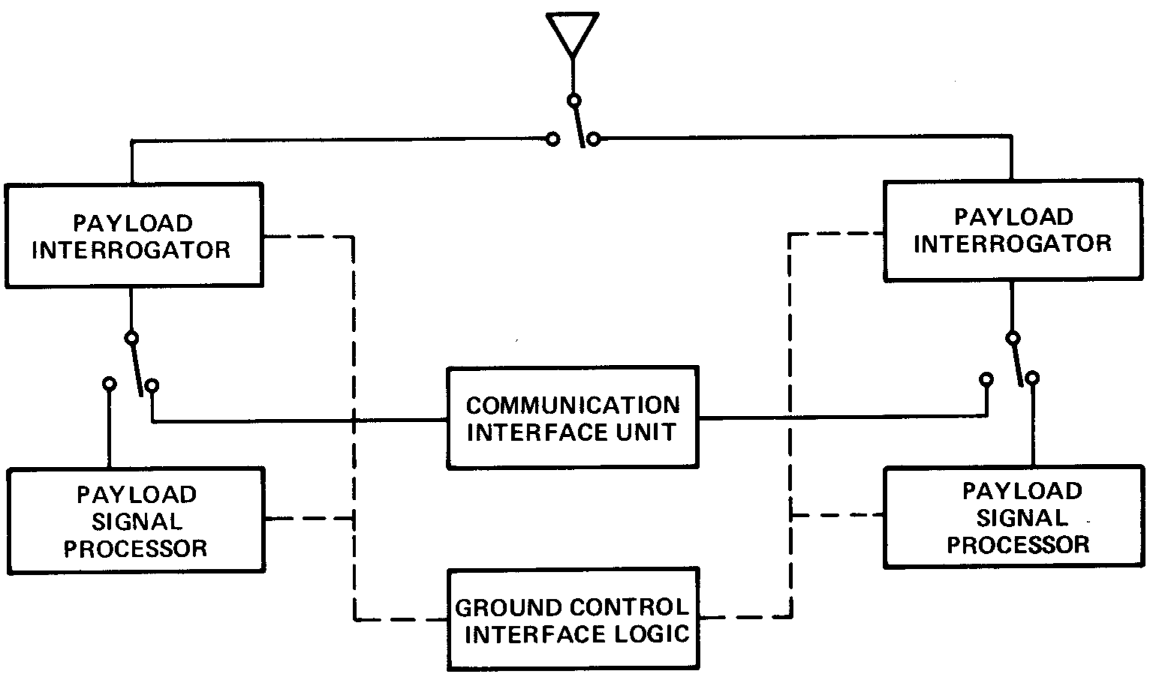


Figure 12. Payload Subsystem Block Diagram

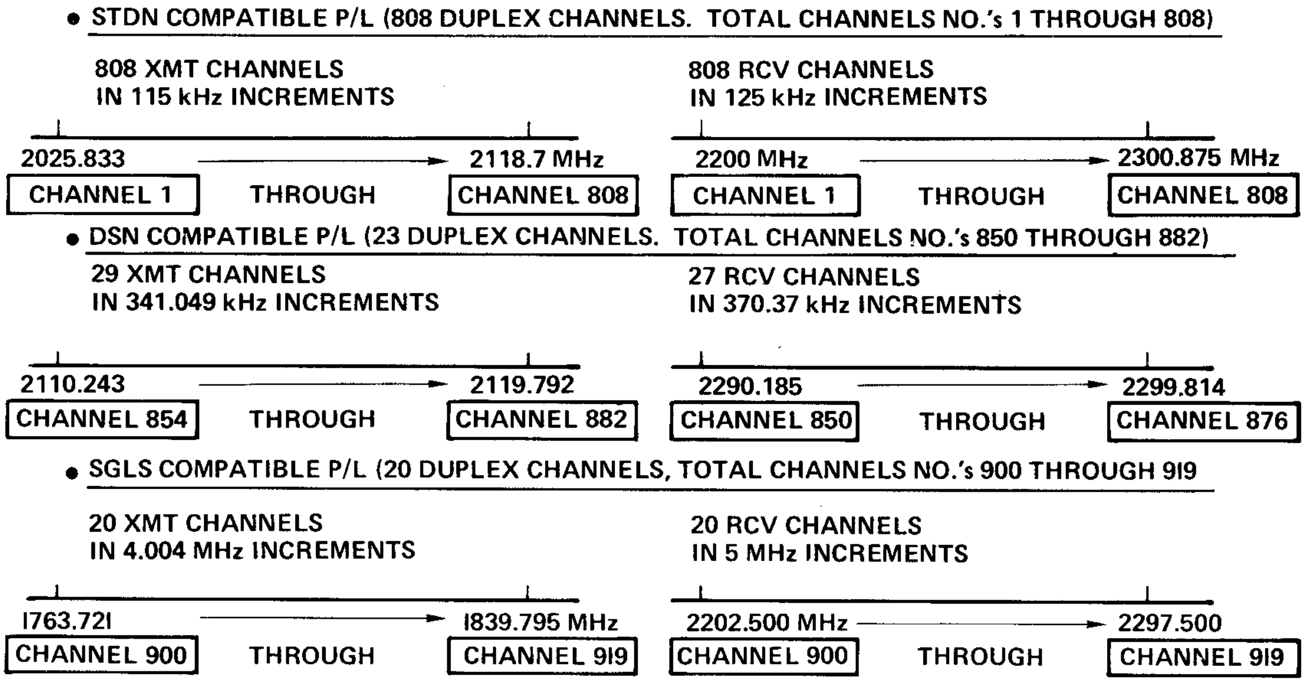


Figure 13. Payload Interrogator RF Channels

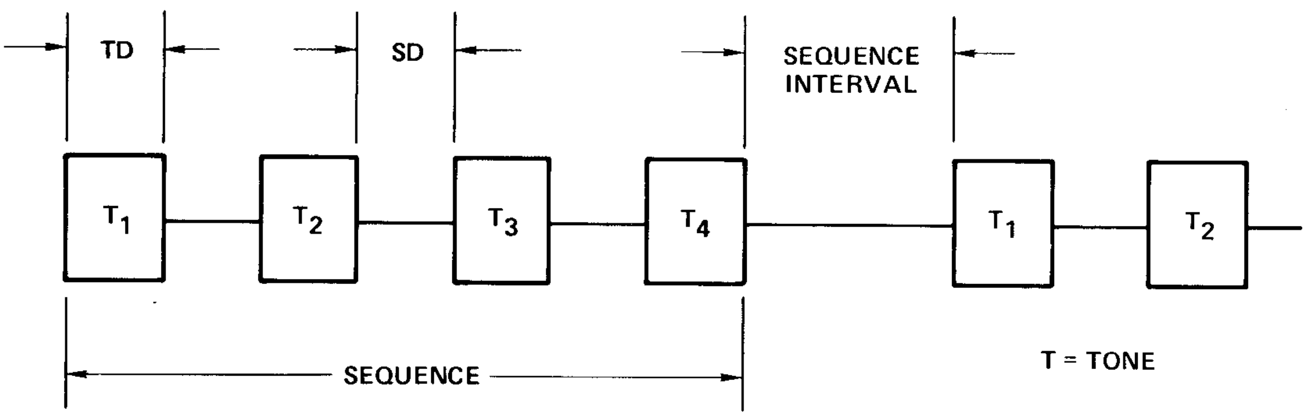


Figure 14. NRZ Sequence Keying

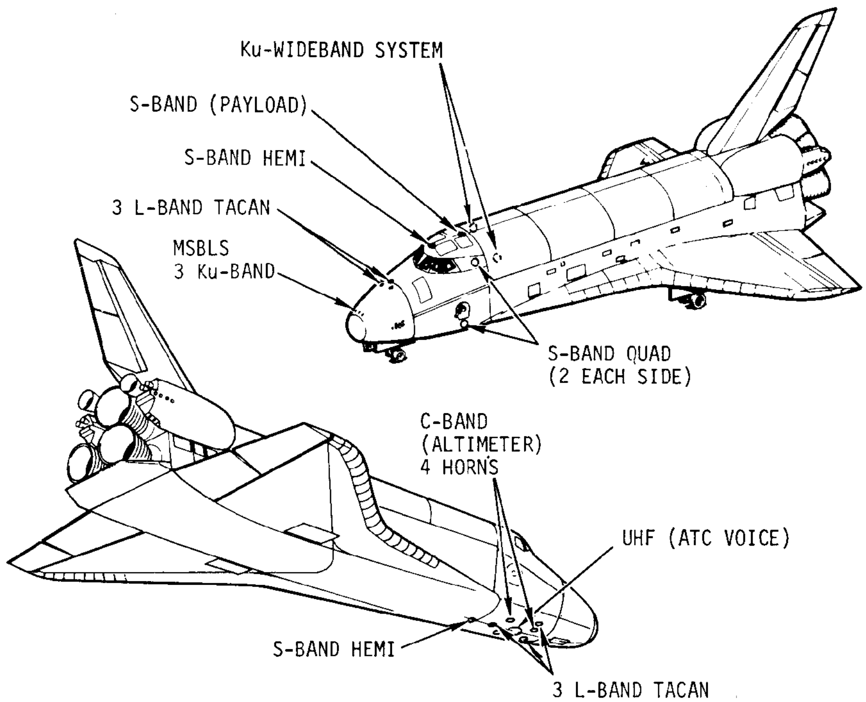


Figure 15. Antenna Locations

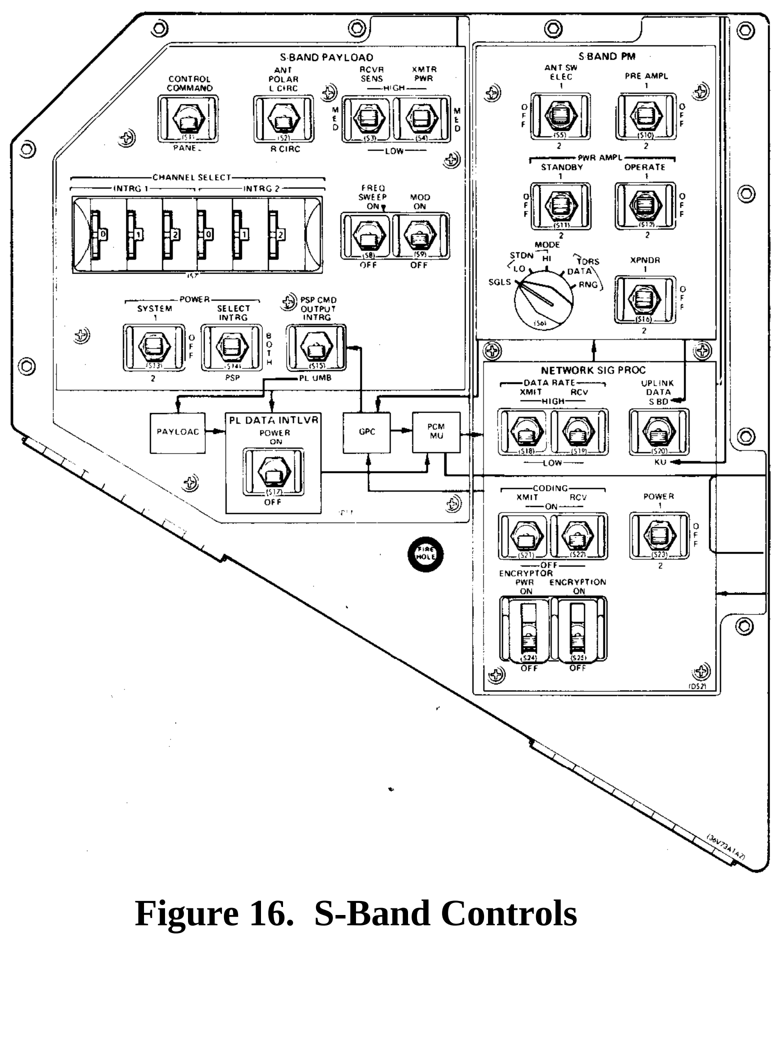


Figure 16. S-Band Controls

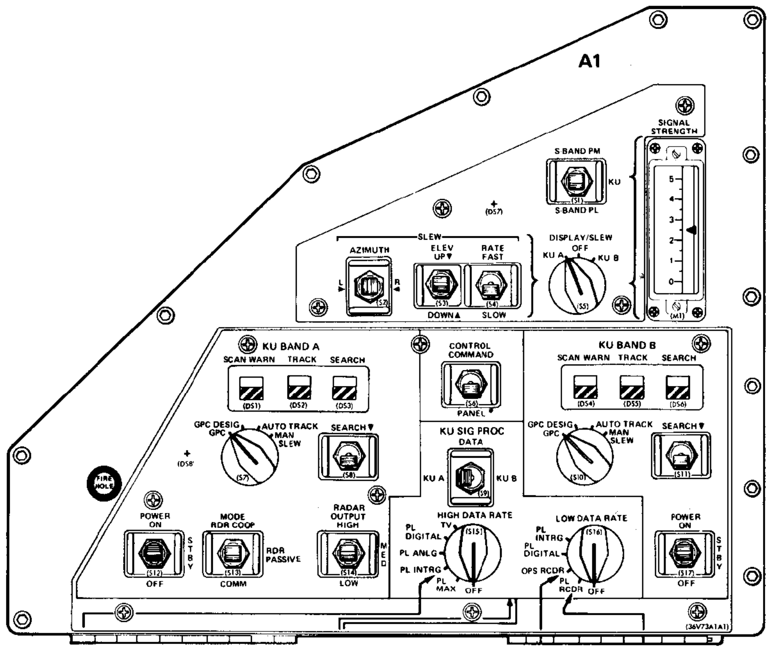


Figure 17. Ku-Band Displays and Controls

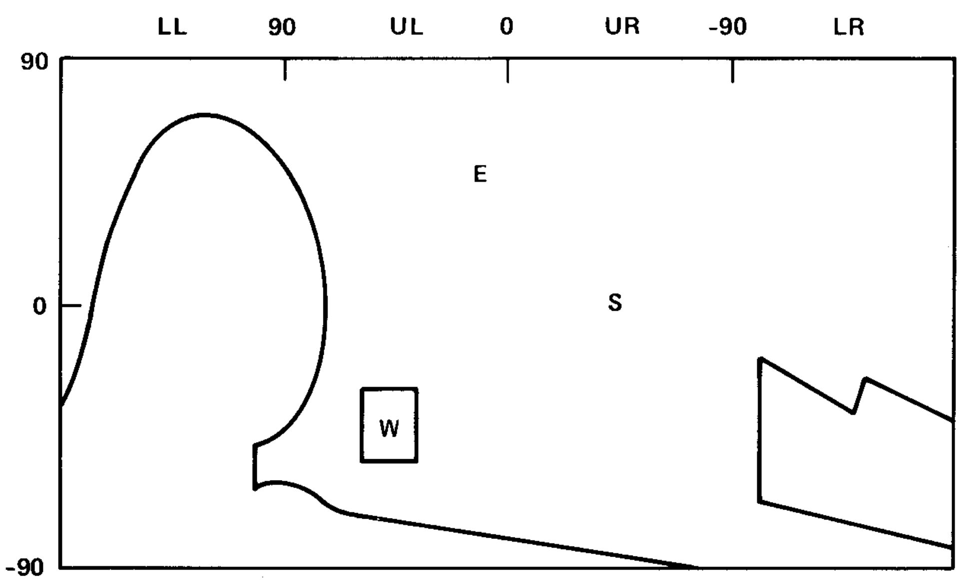


Figure 18. Antenna Display

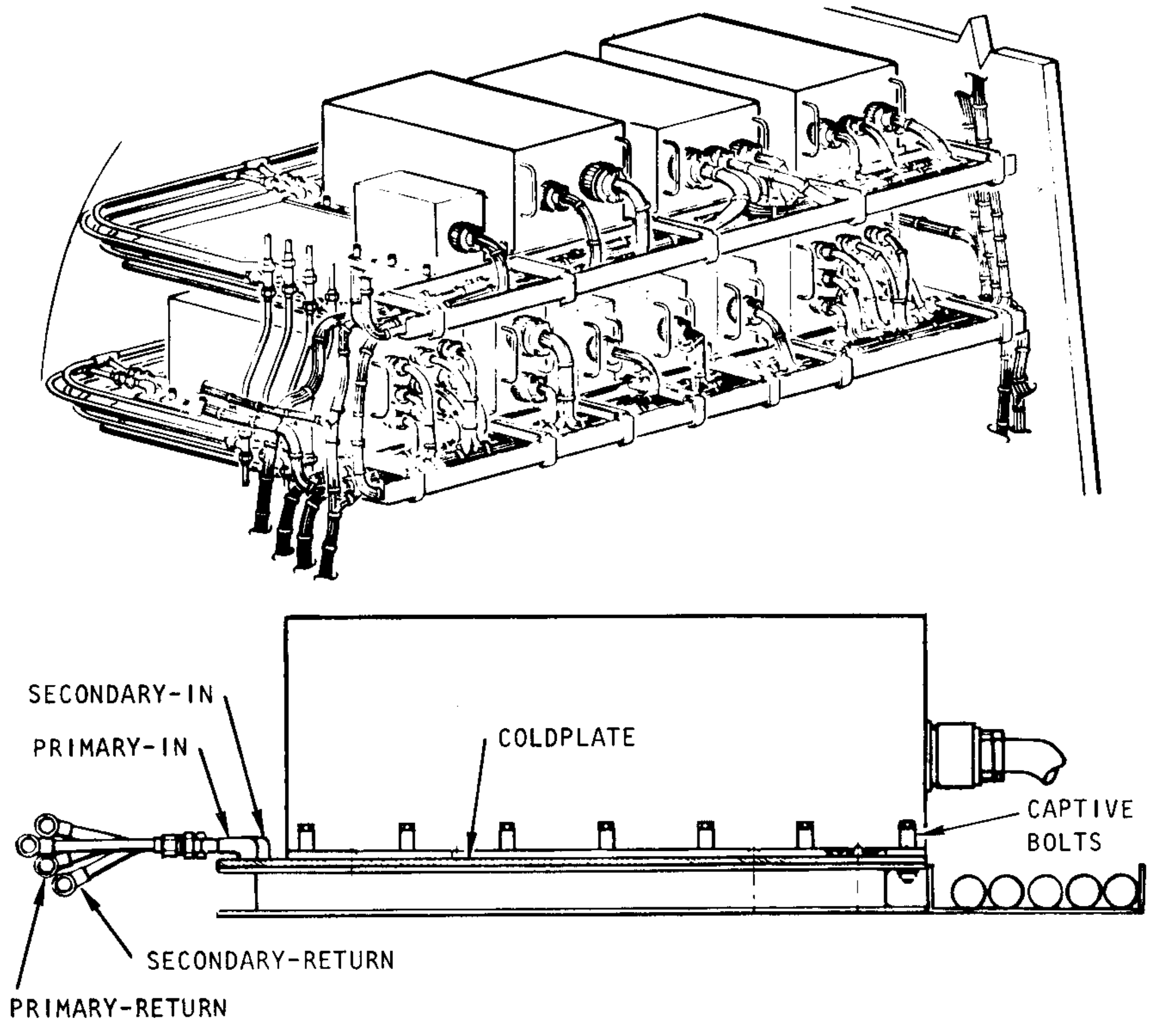


Figure 19. Typical Avionics Installation