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SERT II COMMUNICATIONS SYSTEM DESIGN

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SUMMARY

This report is a description of the communications system as utilized by the Space Electric Rocket Test II (SERT II) spacecraft. The communications system is composed of a PCM-FM-PM telemetry downlink and a multitone-AM command uplink. The communications system is compatible with the Space Tracking and Data Acquisition Network (STADAN) managed by Goddard Space Flight Center (GSFC) which is responsible for data acquisition and commanding of the SERT II spacecraft. Design calculations are included in the following areas: error analysis, bandwidth calculations, radiofrequency link calculation, and antenna system design. The systems' configuration are described which includes the system type and function, signal flow, and the spaceborne-ground compatibility requirements. The component descriptions include the type, function, specifications, and compatibility requirements where necessary. Also described in this report is the unique type of verify system which permits verification of a command, via telemetry, prior to its execution. To date, the communications systems have performed per the design calculations. Of the 2873 commands transmitted to date, the spacecraft did not respond to 0.104 percent of the commands.

INTRODUCTION

The SERT II flight program is a 6-month continuously operational life test of a mercury bombardment ion thruster system. The conduct of the mission requires that experiment and housekeeping data be transmitted to the SERT II Control Center (SCC) for analysis. It is also necessary to operate the equipment aboard the spacecraft which requires that commands be transmitted to the spacecraft from a remote tracking station. The telemetry and command system must be compatible with the Space Tracking and Data Acquisition Network (STADAN) which is managed by Goddard Space Flight Center (GSFC). Goddard is responsible for data acquisition, transmission of real time data to the SCC, and commanding of the spacecraft.

This report presents a description of the SERT II telemetry systems operation which is followed by descriptions of each of the telemetry system components and their operation in the system. The communications systems requirements are presented in this report as background for the design of the system. An error analysis is included using both the root sum of squares (RSS) and worst case method of analysis. A unique feature of the SERT II command system is ground command verification prior to execution of a command. This is described generally for the complete command system operations and in detail in the individual component descriptions. The description of the radiofrequency (rf) system components is preceded by the general system description. Also included in the rf system section are the telemetry bandwidth design, the rf link calculations, and the antenna system design information.

BACKGROUND

The SERT II communications system is required to gather the instrumentation and status outputs from the experiments and telemeter them in real time to the SCC via the STADAN and NASA Communications Network (NASCOM) ground networks. The communications system is compatible with both the STADAN and NASCOM ground networks with a minimum of program peculiar modifications.

The telemetry system requirements are

(1) Command verification signals to the SCC in real time

(2) Data storage during that part of an orbit which STADAN coverage is unavailable

(3) A cumulative telemetered indication of spacecraft time for real time and stored data streams to be correlated to ground time references

(4) A means of calibration of the data handling system

(5) Synchronizing pulses for experiments on-board the spacecraft

The command requirements are

(1) Real time command control of the SERT II spacecraft from the SCC

(2) Ground verification of a command shall be accomplished prior to the execution of that command

(3) The command send rate shall be one command every 5 seconds or faster

The rf system requirements are

(1) Acceptable coverage over at least 90 percent of the radiation sphere

(2) The frequency of operation shall be as follows:

Telemetry, MHz	136 to 137
Command, MHz	148 to 149

(3) The antenna system shall be contained within the spacecraft structure or on the outer circumference of the structure.

DATA HANDLING SYSTEM

General Description

The data handling system is composed of three frequency multiplexed channels which modulate a 350-milliwatt phase modulated transmitter. The first channel (560-Hz center frequency) is modulated by a command verify signal in an 11-bit Return to Zero (RZ) format transmitted at 8.75 bits per second (bps). The second channel (2.3-kHz center frequency) is modulated by the real time telemetry in a Nonreturn to Zero-Change (NRZ-C) format transmitted at 35 bps. This pulse code modulation (PCM) telemetry system has a capability of 240 subcommutated, 5 commutated, and 6 supercommutated channels of housekeeping and experiment data. Calibration voltages are applied to the subcommutators to verify proper operation of the telemetry components and improve the system accuracy. The third channel (5.4-kHz center frequency) is modulated by the spacecraft tape recorder playback data in a NRZ-C format at 560 bps. This data is recorded at a remote tracking station for transmission to the SCC.

The data multiplexing system is composed of four 60-channel pulse amplitude modulation (PAM) subcommutators which are four of the sixteen inputs to the PCM multicoder. The multicoder performs as main commutator, multiplexer, and analog to digital (A/D) converter. The PCM outputs are routed to the inputs of both the Inter Range Instrumentation Group (IRIG) channel 7 (2300-Hz center frequency) voltage controlled oscillators (VCO's) and the tape recorders.

The tape recorder is a frequency modulated (FM) type instrument capable of recording data for 144 minutes and playing it back in less than 9 minutes (16-to-1 reproduce to record speed ratio). The tape recorder output is first passed through a 560-hertz filter (to limit the spectral occupancy) and then into the IRIG 10 (5.4-kHz center frequency) VCO. The three VCO's are then combined in a mixer amplifier and routed to the desired transmitter through a modulation select relay. Figure 1 is a simplified block diagram of the data handling system.

The experiment and housekeeping data is divided among four subcommutators. With this arrangement, it is possible to receive sufficient spacecraft data to support the mission with any three operating subcommutators.

Component Descriptions

Subcommutator. - The four subcommutators utilized for the SERT II mission are identical solid state devices. Each subcommutator has 60 channels; they are arranged as follows. The outputs of the first 15 input gates are connected and then gated through a "transfer" gate. The other three groups of input gates are arranged similarly. The outputs of the four transfer gates are connected and then fed to an operational amplifier to achieve a high input impedance with a low output impedance. A transfer gate provides isolation to protect against an input gate shorting and loading all 60 channels of the subcommutator. The subcommutators also contain the timing circuits to utilize the channel increment pulses and reset pulses from the multicoder to control the input and transfer gates. Two of the subcommutators operate at one sample per second, while the other two operate at one sample per 4 seconds. The minimum output impedance of 4.7 kilohms is due to the resistive isolators utilized to protect each multicoder's input from a short on the other multicoder's input.

Multicoder. - The PCM multicoder is a solid state commutator-coder for both analog and digital information (fig. 2). The multicoder is essentially a 60-channel commutator with a frame rate of once per 12 seconds. The multicoder provides an input for five parallel digital words. One word is assigned to the main frame and the other four are assigned to subcommutator 2 (1/4 min) for the time code word. The multicoder contains the prime oscillator and countdown circuits to control its functions and also control the subcommutators and spacecraft experiments. The major functions of the multicoder are analog multiplexer, digital multiplexer, A/D converter, timing control, and output isolation. The analog multiplexer is similar to the subcommutators, with the exception that only four input gates are connected to each transfer gate.

Frequency division multiplex. - The frequency division multiplex assembly is composed of two each of IRIG 2, IRIG 7, and IRIG 10 VCO's and two each mixer amplifiers mounted on a chassis as shown in figure 3. The chassis contains the adder isolators from each VCO to each of the mixer amplifier. The 8.75-bps command verify signal in an RZ format modulates the IRIG 2 VCO. The IRIG 7 VCO is modulated by the operating multicoder's filtered, 35-bps, output signal. The IRIG 10 VCO is modulated by the output of the on-board tape recorder at 560 bps. A filter is inserted between the IRIG 10 VCO and the tape recorder to limit spectral occupancy.

The frequency division multiplex subassembly thus is composed of 6 VCO's (two associated with each input signal, one of each pair redundant) and one output isolator. The operational mode is such that each VCO (when it is active) feeds two adder isolators. Three VCO's (one for each signal input type) are active at a time. This results in two independent frequency multiplexed signals (at each adder isolator output) for application to the respective mixers. The active mixer provides an amplified signal to the output isolator, which in turn provides two isolated outputs to the modulation select relay.

Tape recorder and filter. - The tape recorders as utilized for SERT II are two-track, reel-to-reel, FM instruments (fig. 4). Two redundant recorders are provided. They have the capability of recording for approximately 144 minutes and playing this information back in less than 9 minutes. This results in a reproduce to record speed ratio of 16 to 1. The 35-bps NRZ-C data is speeded up by that ratio and appears as 560-bps NRZ-C output of the recorder. Each of the unfiltered PCM outputs of the multicoder in use is applied to both tracks of the recorder. The track utilized is determined by the track select relay which selects the playback data on either track 1 or track 2. The same track is selected for both recorders. The 560-bps PCM signal is then fed to the 560-Hz filter which limits the spectrum cutoff at 560 hertz with a roll off of 18 decibels per octave. Also provided in the filter is an isolation network. The operational mode is such that, for either recorder in playback (the other being off), two output signals are obtained from the isolator for the two VCO's, one of which is redundant.

Modulation select. - A relay is provided to select the transmitter to be modulated from the isolated mixer outputs. This relay acts as a switch to transfer both mixer outputs (only one of the mixers being on) to both modulation inputs of the selected transmitter. A status monitor is provided to indicate the transmitter selected.

Calibrator. - A solid state dc-dc converter is provided as a calibration source of 2.46 and 5.002 ± 0.01 volts. This is provided to evaluate the errors incurred in multiplexing and A/D conversion. Decimal counts of 30 and 61 are obtained at the A/D converter output for these two signals, respectively. The calibrator consists of an input series regulator, a transformer converter, and an output series regulator and filter.

Time code generator. - The time code generator (TCG) is a solid state internal counter which provides cumulative satellite time to telemetry and a clocking signal for command memory readout. The TCG is utilized to provide time verify correlation for both real time and playback data. The time code consists of five decimal characters and is updated at the start of each major frame (every 4 min), thus providing a maximum cumulative time count of 277 days (4 min × X 99 999). The time code decimal characters are brought out on 20 lines (4 bits per character) which are sampled once every 4 minutes by the multicoder. The TCG also has provisions for accepting three commands: zero reset, up count, and down count. In addition, the TCG provides a 17.5-pulse-per-second square wave signal for the command verify readout. The TCG consists of a regulated power supply, a crystal oscillator (stability, ±0.01 percent), a binary countdown chain (143.6 kHz down to 1 pulse/4 min), and an output Binary Coded Decimal (BCD) register.

Telemetry Error Analysis

General. - The analysis attempts to include all significant error sources, with the exception of the transducers, signal conditioning, and final analog display device, since these errors depend on the type of instrumentation channel involved. Typical values were assumed for the first two types of error sources at the conclusion of each analysis in an attempt to give a better understanding of the total overall error involved. Overall system errors of 1.59 and 3.35 percent of full scale were obtained for the RSS and worst case approaches, respectively.

The error model of the telemetry system which was used in both cases is shown in block diagram form in figure 5. The model considers all data handling and processing operations to be in a series arrangement between input and readout. Error characteristics of the data handling elements involved are shown in table I.

Root sum of square method. - This approach combines the worst case error contributions of the equipment by RSS. The subcommutator effective error signal contribution E_1 is

$$E_1 = \sqrt{(V_b)^2 + (V_k)^2 + (V_o)^2 + (V_s)^2 + (V_x)^2 + (V_1)^2 + (V_n)^2 + (V_z)^2} \qquad (1)$$

where

V_b	error due to back current, $I_b Z_{out} = (0.3\times10^{-6}\ \mathrm{A})(5\times10^{3}\ \Omega) = 1.5\ \mathrm{mV}$
V_k	error due to nonunity gain, $(5000\ \mathrm{mV})(0.0005) \approx 2.5\ \mathrm{mV}$
V_o	offset error, $\pm2\ \mathrm{mV}$
V_s	scatter error, $\pm500\ \mu\mathrm{V}$
V_x	crosstalk error, $(0.001)(5000\ \mathrm{mV}) = 5\ \mathrm{mV}$
V_1	linearity error, $(5000\ \mathrm{mV})(0.0005) = 2.5\ \mathrm{mV}$
V_n	internal noise error, $\pm2\ \mathrm{mV}$
V_z	error due to nonzero data output impedance,

$$\left(5000\ \mathrm{mV}\right)\left(\frac{Z_{out}}{Z_{out} + Z_{in}}\right) = \left(5000\ \mathrm{mV}\right)\left(\frac{5\times10^{3}\ \Omega}{5\times10^{3}\ \Omega + 5\times10^{7}\ \Omega}\right) \cong 0.5\ \mathrm{mV}$$

and

I_b	back current
Z_{out}	output impedance, Ω
Z_{in}	input impedance, Ω

Then

$$E_1 = \sqrt{(1.5)^2 + (2.5)^2 + (2)^2 + (0.5)^2 + (5)^2 + (2.5)^2 + (2)^2 + (0.5)^2}$$

$$= \sqrt{48.25}$$

$$= \pm 6.95 \text{ mV}$$

The effective error signal contribution due to the PCM multicoder E_2 is

$$E_2 = \sqrt{(V_b)^2 + (V_k)^2 + (V_o)^2 + (V_s)^2 + (V_x)^2 + (V_1)^2 + (V_n)^2 + (V_z)^2 + (V_q)^2} \qquad (2)$$

where

V_b	back current error, $I_b Z_{out} = (0.3 \times 10^{-6})(20) = 6\ \mu V$
V_k	nonunity gain error, $(5000 \text{ mV})(0.0005) = 2.5 \text{ mV}$
V_o	offset error, ± 2 mV
V_s	scatter error, $\pm 500\ \mu V$
V_x	crosstalk error, $(0.001)(5000 \text{ mV}) = 5 \text{ mV}$
V_1	linearity error, $(5000 \text{ mV})(0.0005) = 5 \text{ mV}$
V_n	internal noise, ± 2 mV
V_z	error due to nonzero subcommutator output impedance, $\left(5000 \text{ mV}\right)\left(\frac{Z_{out, subcom}}{Z_{out, subcom} + Z_{in}}\right) = \left(5000 \text{ mV}\right)\left(\frac{4.7 \times 10^3\ \Omega}{5 \times 10^7\ \Omega + 4.7 \times 10^3\ \Omega}\right) = 0.47 \text{ mV}$
V_q	quantizing error, $(5000 \text{ mV})(0.004) + 41 \text{ mV} = 61 \text{ mV}$

and

$Z_{out, subcom}$	subcommutator output impedance, Ω

Since V_b is relatively small, it is neglected and

$$E_2 = \sqrt{(2.5)^2 + (2)^2 + (0.5)^2 + (5)^2 + (2.5)^2 + (2)^2 + (61)^2 + (0.47)^2}$$

$$= \pm 61.4 \text{ mV}$$

The combined error, due to the subcommutator and multicoder, is

$$E_3 = \sqrt{(E_1)^2 + (E_2)^2} = \pm 61.8 \text{ mV} \tag{3}$$

The rf communications link transfers the digital data from the multicoder to the ground system equipment with a bit error rate of 1 bit in 10^6 in the real time mode or 1 bit in 10^5 in the recorder playback mode. Considering the parity check bit, best available information indicates that rms analog errors introduced by these bit error probabilities does not exceed 0.01 percent; their effect on the system error is therefore neglected.

The ground readout equipment, neglecting the final analog display device, introduces error only after the D/A conversion in the linearity error of the D/A converter. Calling this error source V_L gives

$$V_L = \text{D/A linearity error} = (0.001)(5000 \text{ mV}) = 5 \text{ mV}$$

The total error is

$$E_T = \sqrt{(61.8 \text{ mV})^2 + (5.0 \text{ mV})^2} \cong \pm 62.0 \text{ mV} \tag{4}$$

This total error corresponds to 1.24 percent of the 5-volt full-scale signal, but does not include the error contributions of sensor, signal conditioning, or analog display device. By denoting the first two of these in millivolts by V_S/V_C, respectively, the overall system error would be

$$E_S = \sqrt{(62.0 \text{ mV})^2 + (V_S \text{ mV})^2 + (V_C \text{ mV})^2} \tag{5}$$

In an attempt to give a more complete picture of the total system error, "typical" values were assigned to the remaining error values as follows:

$$V_S = \pm 0.707 \text{ percent} = (0.00707)(5000 \text{ mV}) = 35 \text{ mV}$$

$$V_C = \pm 0.707 \text{ percent} = (0.00707)(5000 \text{ mV}) = 35 \text{ mV}$$

The overall system error is then

$$E_S = \sqrt{(62.0\ \mathrm{mV})^2 + (35\ \mathrm{mV})^2 + (35\ \mathrm{mV})^2} \doteq \pm 79.6\ \mathrm{mV}$$

Thus, when typical sensor and signal conditioning error contributions are included, the system RSS error is 1.59 percent of full scale.

Worst case method. - This approach considers all the error sources being simultaneously maximum in the same direction, so that all sources add directly. The error sources are retabulated in table II.

If typical values are assigned to sensor and signal conditioning as in the RSS approach, a total overall system worst case error is obtained, that is,

V_S =	0.7 percent
V_C =	0.7 percent
	1.4 percent
Other sources from table II	1.95 percent
Total system error	3.35 percent

COMMAND SYSTEM

General Description

The command system for the SERT II spacecraft is the STADAN multitone-AM system. The system contains two redundant receivers operating at the same frequency, a command decoder with redundant power supplies to permit decoding 108 commands from each "half" of the decoder, and the command verify circuitry (fig. 6). One unique address tone with a combination of three of six command tones comprise the system which provides 216 separate or 108 redundant commands. A unique feature of the system is ground command verification prior to execution of a command. This is accomplished by the 560-hertz channel of telemetry in which the signal, when decoded, displays the command number transmitted to the spacecraft. During the verification time, the command is stored in the decoder. Upon positive verification, the command is then executed by transmission of the address tone. The total number of commands utilized for SERT II is 144; of these, 72 have backups.

A valid command consists of the SERT II address tone followed by any combination of the six system command tones. The tone burst occur every second with a duration of 0.5 second, so that the time envelope of the command is 4 seconds. Since the identity of any command is determined by the particular combination of three tones involved, the system has a capacity of 6^3 or 216 commands.

Component Descriptions

Receiver. - The receivers utilized for SERT II are solid state units which receive in the 148-megahertz frequency band (fig. 7). The received command transmission is demodulated, and the audio tones from the demodulator are delivered to one of the redundant inputs of the decoder for processing.

The receiver characteristics are as follows:

Frequency band, MHz	148
Noise figure, dB	8
Minimum sensitivity (at 10-dB SNR), dBm	-101
Image rejection, dB	80
Spurious response, dB	-60
IF bandwidth, kHz	
Minimum (at -6 dB)	35
Maximum (at -60 dB)	110
Output bandwidth (±2 dB), kHz	1 to 7
Local oscillator stability, kHz	±2
Standby power (at 28 V dc), mW	450
Interrogate power (at 28 V dc), mW	700
Size, cc	356
Weight, kg	0.73

Decoder. - The decoder (fig. 8) receives the demodulated tone messages, converts the tone format into digital symbols, and stores the digital version of the command received in a solid state memory. The decoder inhibits execution of the command until the address tone is received again, permitting ground verification of the stored command. The memory is automatically cleared at the end of 12.5 seconds, or it may be cleared by ground command in the event the stored command was in error. Protection is provided against spurious signals or improper formats in that:

(1) The tones received must be between 200 and 800 milliseconds in length.

(2) Spacing between tones must be between 200 and 800 milliseconds.

(3) A tone may not occur during the normal off interval.

(4) A tone may not be missing from the normal four-tone pattern.

In addition, the decoder is protected against excessive current drain in both the B+ regulator and output matrix, such as is caused by a short-circuited output load. Excessive current levels deenergize the B+ from the decoder.

When the decoder receives an execute command, an output signal is sent through the appropriate pair of output relay driver lines into the command distribution unit. There, redundant command outputs are interconnected. Some of the command pulses operate latching relays for power switching of components and also provide status monitors and signal conditioning for the monitors.

As each command tone is identified by the decoder, a code number is present on three output lines associated with that tone, that is, tone 1, 2, or 3. This results in nine parallel lines from the decoder to the command junction box where the verify circuitry is located.

Verify system. - The verify system for SERT II performs in the following manner. As each command tone is identified, it is coded and presented to the verify circuitry. After the second execute tone is identified, the presence of a tone code (1 to 6) starts the verify clock which divides the 17.5 pulse per second from the time code generator by two resulting in 8.75 pulse per second to operate the verify circuitry.

The first bit transmitted is a synchronizing (sync) bit followed by the three bits identifying tone number 1; next are the three bits identifying the second tone; and then the three-bit code for the third tone. The final bit in the stream is a parity bit which is "up" to make an odd number of bits (sync bit excluded). Figure 9 illustrates the command timing and verify format.

The verify format is as follows:

Bit	Function	
1	Sync	
2	Binary 4	Tone 1
3	Binary 2	
4	Binary 1	
5	Binary 4	Tone 2
6	Binary 2	
7	Binary 1	
8	Binary 4	Tone 3
9	Binary 2	
10	Binary 1	
11	Parity	

Two isolated outputs are provided to drive the operating IRIG 2 VCO.

The telemetry decoder at the SCC turns on at the presence of the first binary 1 (sync bit). This turns on a delay oscillator to verify that a binary 1 is still present 1/4 pulse later. If not, the ground decoder turns off. With the binary 1 still present, a sampling clock is turned on which deciphers the verify signal. The binary code is converted to decimal numbers and the tone sequence is then presented on an illuminated display. Upon positive verification, the address tone is retransmitted to "execute" the stored command. The minimum time to transmit and enable a command is 4.5 seconds; however, this does not allow time to verify the command. The maximum time allowable to transmit and execute the command is 16.5 seconds before the automatic clear resets the decoder memory.

RADIOFREQUENCY SYSTEM

General Description

The SERT II rf system consists of the two receivers discussed previously, two phase modulated transmitters, two diplexers, three hybrids, four quarter wave monopole antennas, and the necessary cables and phasing lines (fig. 10).

A transmitter and a receiver are connected to each diplexer. Both diplexers are connected to the main hybrid, which in turn is connected to the output hybrids. The antennas then connect to the two hybrids through appropriate length phasing cables.

The SERT II transmitters radiate telemetry information continuously from the quarter wave monopole turnstile array. Normally, only one transmitter is on with the other being a standby unit. Sufficient power has been left in the carrier to permit interferometer tracking of the spacecraft for orbit determination.

Component Descriptions

Transmitters. - The SERT II transmitters are solid state phase modulated units providing a minimum of 350 milliwatts of rf power to the antenna system (fig. 11). Both transmitters are identical except for carrier frequency. Both transmitters operate at different frequencies in the 136- to 137-megahertz band. The transmitters consist of the following systems: regulated power supply, oscillator, modulator, frequency doubler, power amplifier, and filter. The following characteristics apply to the transmitter:

Frequency band, MHz	136 to 137
Frequency stability, percent	±0.003
Output power, mW	350 (min)
Frequency response, Hz	350 to 3×10^4
Phase stability	Within 0.25 rad
Spurious response, dB	60 (min)
Load VSWR	1.5 to 1 (meets all specifications); 5 to 1 (survives without damage)

Diplexer and hybrids. - Each diplexer provides a 40-decibel isolation between the transmitter and receiver at 136 megahertz. Each of three hybrids provides 20 decibels of isolation at 149 megahertz and 35 decibels at 136 megahertz between the isolated ports. The insertion loss between input and output ports of the hybrid is less than 3.25 decibels at 136 megzhertz and 3.4 decibels at 149 megahertz.

Antenna system. - The antenna system consists of four quarter wave monopoles phased to provide right circular polarization towards earth with normal spacecraft attitude. The antennas are arranged as dipoles operating from each output hybrid. This results in the 0° phased stub and the -180° phased stub operating from the first output hybrid and the -90° stub and -270° stub operating from the second output hybrid. This formation will essentially allow the radiation of a dipole pattern in the event of a failure of one stub. The stub 180° from the failed one will provide some fill-in to the pattern.

Radiofrequency System Design

This section documents the design calculations and constraints which led to the SERT II communications system rf link operating parameters and design configuration.

Bandwidth. - STADAN frequency standards require that users of the 136-megahertz frequency band for telemetry purposes shall not exceed the assigned 30-kilohertz channel bandwidth at the 10-decibel points. In addition, it is required that the transmitted spectrum outside the assigned channel band edges must fall off at 18 decibels per octave. The constraint of 30-kilohertz allowable rf bandwidth served as a primary starting point for the system design.

Frequency variations: The useable spacecraft transmitter bandwidth is less than 30 kilohertz by the variations in transmitter frequency apparent to the ground station. The most important sources of these variations are Doppler frequency shift and transmitter instability.

The Doppler shift is computed from

$$\Delta f = \frac{V}{C} f_t \tag{6}$$

where

Δf maximum instantaneous received frequency shift

V maximum velocity of source relative to observer, $\cong 6.36 \times 10^3$ m/sec

C velocity of light, 3×10^8 m/sec

Then, f_t transmitted frequency, 137 MHz

$$\Delta f = \left(\frac{6.36 \times 10^3 \text{ m/sec}}{3 \times 10^8 \text{ m/sec}}\right)(1.37 \times 10^8 \text{ Hz}) \cong \pm 2.9 \text{ kHz}$$

The transmitter instability of the SERT II transmitter is ±0.003 percent of the assigned frequency. Thus, a worst case shift would be about $(0.00003)(1.37 \times 10^8) = \pm 4.11$ kilohertz.

The worst case ground-observed frequency shifts would occur when the aforementioned two effects add, giving rise to a shift of $\approx \pm 7.0$ kilohertz. Consequently, the maximum remaining bandwidth in a 30 kilohertz assigned channel is 30 kilohertz - 2(7.0) = 16 kilohertz. Allowing for ±750 hertz to avoid distortion at the receiver band edges and ±750 hertz for receiver stability, the available bandwidth for transmission is further reduced to approximately 13 kilohertz.

With the usable bandwidth established at 13 kilohertz, an upper limit is set on the highest frequency subcarrier than can be used in a frequency division multiplex system, since the first sideband can be displaced from the carrier by no more than half the available bandwidth. Thus, no subcarrier higher than an IRIG 10 (5.4 kHz) can be used.

Frequency division multiplex: In order to avoid the development cost of the on-board data processing equipment, the decision was made to use subcarrier oscillators. The three sources of data on the SERT II spacecraft have bit rates of 8.75 bps (NRZ), 35 bps (NRZ-C), and 560 bps (NRZ-C).

Since the highest IRIG subcarrier which can be used is a number 10, the 560-bps data were assigned to this channel. The 35- and 8.75-bps data streams were assigned to channels 7 and 2, respectively. The required frequency responses and resulting modulation indices are summarized as follows for the three subcarriers:

IRIG 10

$$MI = \frac{\Delta F}{F_m} \tag{7}$$

where

MI modulation index

ΔF zero to peak deviation of subcarrier

F_m maximum modulating frequency

Then

$$F_m = \frac{\text{Bit rate}}{2} = \frac{560}{2} = 280 \text{ Hz} \qquad \text{(NRZ-C data)}$$

and

$$MI = \frac{405}{280} \cong 1.45$$

IRIG 7

$$F_m = \frac{\text{Bit rate}}{2} = 17.5 \text{ Hz} \qquad \text{(NRZ-C data)}$$

$$MI = \frac{173}{17.5} = 9.86$$

IRIG 2

$$F_m \cong 3(\text{Bit rate}) = 26.2 \text{ Hz} \qquad \text{(RZ data - no filtering)}$$

$$MI = \frac{42}{26.2} = 1.6$$

The frequency response for IRIG 7 and 10 is taken as one-half of the bit rate because an alternate one-zero bit pattern will produce a square wave for every two bits. Low pass filters with cutoff at the bit rate are used on channels 7 and 10, so that only the first harmonic is passed.

The IRIG 2 data are unfiltered to permit the maximum rise time of the data. Also, the low duty cycle of modulation to this VCO influenced the decision not to use a filter. Since the data are unfiltered, their frequency response includes the third harmonic of the 8.75-bit rate. The standard $7\frac{1}{2}$ percent deviation is used on all channels. It is standard practice to use a modulation index of 2 for coded data, although any index greater than one will allow a standard subcarrier discriminator to encompass the first sidebands of the modulating signal.

Transmitter modulation: The choice of transmitter modulation index is dictated both by the desire to place most of the spectral energy in the 13-kilohertz bandwidth available and at the same time maintain sufficient energy at the carrier frequency to meet the beacon tracking signal requirements of the STADAN Minitrack system. In addition, an upper limit of ~1.10 radians rms deviation is imposed by the phase demodulator in the ground station to avoid loss of phase lock. In consideration of the aforementioned factors and the following analysis, the transmitter phase deviation was set at 1 radian rms.

For a phase modulated (PM) system, the modulation index of each subcarrier should be proportional to the square root of the channel bandwidth, if equal signal to noise ratios (SNR's) at the discriminator outputs are to be maintained. Combining this requirement with a 1-radian-rms total modulation level gives the following modulation indices (peak phase deviation) for the three subcarriers:

IRIG channel 2 : $\Delta\theta_2 = 0.37$ radians peak
IRIG channel 7 : $\Delta\theta_7 = 0.75$ radians peak
IRIG channel 10 : $\Delta\theta_{10} = 1.14$ radians peak

The fraction of total power retained in the carrier is

$$\frac{P_c}{P_T} = \left[J_0(\Delta\theta_2)\, J_0(\Delta\theta_7)\, J_0(\Delta\theta_{10})\right]^2 = 0.342 \text{ (-4.6 dB)} \tag{8}$$

where

P_c	carrier power
P_T	total power
$J_0(\Delta\theta)$	Bessel's coefficient of order zero

The usable subcarrier fractional power is given by

$$\frac{P_{sc}}{P_T} = 2\frac{P_c}{P_T}\left[\frac{J_1(\Delta\theta_{sc})}{J_0(\Delta\theta_{sc})}\right]^2 \tag{9}$$

where

P_{sc} subcarrier power

$J_1(\Delta\theta)$ Bessel's coefficient of order 1

The power fractions for the three subcarriers thus obtained are

$$\frac{P_2}{P_T} = 0.0243 \ (-16.1 \text{ dB})$$

$$\frac{P_7}{P_T} = 0.112 \ (-9.5 \text{ dB})$$

$$\frac{P_{10}}{P_T} = 0.324 \ (-4.9 \text{ dB})$$

In summary, approximately 34 percent of the power remains in the carrier, 46 percent in the usable subcarrier sidebands, and 20 percent is lost in higher order and cross-modulation terms.

The frequency band which contains approximately 99 percent of the rf spectral energy is

$$B = 2f_m(M + 1) \tag{10}$$

where

f_m highest modulating frequency, Hz

M peak transmitter phase deviation, radians

Then

$$B = 2(5.4 \text{ kHz})(1.41 + 1) = 26.1 \text{ kHz}$$

Although this exceeds the 13-kilohertz usable bandwidth discussed earlier, it does not violate the STADAN bandwidth standards. This is shown by figure 12, where the frequency half-spectrum is plotted with the STADAN limitation superimposed. It is also evident that a 30-kilohertz predetection receiver bandwidth is adequate.

Radiofrequency link calculations. - The three VCO channels are phase modulated onto the rf carrier with a total modulation index of 1 radian rms. The portion of transmitted power at the carrier frequency is sufficient for beacon-interferometer operation. Consequently, one transmitter suffices for both the telemetry and the Minitrack tracking beacon functions. The modulation indices of the individual VCO's are 1.14, 0.75, 0.37 radians peak for the IRIG channel 10, 7, and 2 oscillators, respectively.

The rf power budget given in table III(a) is computed for each channel as follows:

$$S_i = P_T + G_T - L_{FS} + G_R - L_G + C_{P8} \tag{11}$$

where

S_i	channel signal level
P_T	transmitter power
G_T	transmitting antenna gain
L_{FS}	free space loss
G_R	receiving antenna gain
L_G	ground system losses
C_{P8}	channel power fraction, i.e., $P_{channel}/P_{transmitter}$

and

$$SNR = S_i - N_i$$

where

S_i = channel signal level

N_i = channel noise level

and

$$\text{Margin} = SNR - \text{threshold}$$

The SNR values shown are those in the discriminator or tracking loop bandwidths. The SNR for IRIG channels 2 and 7 indicates the level of the signal applied to the communications circuit at the ground station for transmission to the SCC. The tracking SNR corresponds to the residual carrier power for tracking in the Minitrack fine measurement channel. The margin for all channels increase by 9.7 decibels near zenith.

Listed in table III(b) is the rf power budget for the command uplink. The 200-watt transmitter with a 10-decibel gain antenna is the STADAN's minimum command configuration, which provides 8 decibels of margin.

Antenna design. - Coverage: A circularly polarized turnstile array of four monopoles was selected for the SERT II antenna system (see fig. 13). This system is utilized for both telemetry and command transmissions. The pattern characteristics of this arrangement were investigated in a study of the one-tenth scale model of the SERT II vehicle. The study showed that the turnstile array was capable of meeting the coverage requirements of 90 percent of the radiation sphere at both frequency regions of interest.

Figure 14 shows the composite antenna pattern obtained from the one-tenth scale model measurements. A summary of the coverage obtained is shown hereinafter. The "composite" case corresponds to the actual polarization diversity situation to be used by the STADAN network, where the larger of the two polarizations is the one selected. It is evident that the -7-decibel-gain figure used in the rf link calculations is exceeded over 90 percent of the radiation sphere.

Polarization	Gain, dB		
	-6	-10	-16
	Coverage, percent		
E_θ (see fig. 14)	84.1	89.3	92.1
E_ϕ (see fig. 14)	83.3	94.5	98.5
Composite	89.9	99.0	99.8

Impedance: The optimum length of the monopoles can be obtained approximately from figure 3-4 in Jasik (ref. 1). The reactance is seen to be zero in the frequency interval of interest for a length of about 82 electrical degrees. This indicates the length of the monopoles to be about one-fourth wave-length at 143 megahertz (center frequency of the interval of interest) reduced by a factor of 82/90, or

$$L = \left(\frac{c}{f}\right)\left(\frac{1}{4}\right)\left(\frac{82}{90}\right) \tag{12}$$

where

c velocity of light, cm/sec

f frequency, Hz

Consequently, the expected optimum length should be approximately

$$L \cong \left(\frac{3\times10^{10}\ \mathrm{cm/sec}}{1.43\times10^{8}\ \mathrm{Hz}}\right)\left(\frac{1}{4}\right)\left(\frac{82}{90}\right) \cong 47.8\ \mathrm{cm}$$

Impedance measurements were taken on the flight model antennas mounted on a full-scale mockup simulating the spacecraft support unit (SSU), the spacecraft, and the first 1.2 meters of the Agena vehicle. The measured values of impedance are plotted in figure 15. It can be seen that a VSWR circle passing through both frequency curves having minimum radius corresponds to an optimum stub length of about 47.6 centimeters.

The impedance was also measured as a function of frequency for a fixed length of 47.8 centimeters and the data are plotted in figure 16. It is evident from these figures that a VSWR of less than 1.5 to 1 can be obtained with no impedance matching network.

From figure 16, VSWR circles of 1.31 to 1 and 1.44 to 1 can be drawn through the points of 136.5 and 149 megahertz, respectively. The efficiency of power transfer to the antenna is given by

$$E = \left[1 - \left(\frac{\mathrm{VSWR} - 1}{\mathrm{VSWR} + 1}\right)^2\right] \times 100\ \text{percent} \tag{13}$$

The indicated efficiencies at the SERT II frequencies are at 136.5 megahertz:

$$E_1 = \left[1 - \left(\frac{0.31}{2.31}\right)^2\right] \times 100\ \text{percent} = 98.2\ \text{percent}$$

and at 149 megahertz:

$$E_2 = \left[1 - \left(\frac{0.44}{2.44}\right)^2\right] \times 100\ \text{percent} = 96.7\ \text{percent}$$

System design considerations: A block diagram of the rf network of the SSU is shown in figure 10. The antenna system is shared by the command and telemetry systems via redundant diplexers. The diplexer outputs are combined in a hybrid to allow either diplexer to function independently with the turnstile array. The four monopoles are fed in pairs with the phasing arrangement shown by two additional hybrids, one for each pair. This arrangement, in conjunction with the phasing scheme used, allows a dipole pattern to be obtained in the event of failure of either hybrid.

The coverage obtained with a dipole pattern is still quite good, as can be seen in figure 17. The only nulls are off the ends of the two active monopoles where the field intensity is below -7 decibels only for polar angle $\theta < 25^{\circ}$. The coverage is given by the solid angle of the null divided by the solid angle in a hemisphere or,

$$\text{Coverage} = \frac{1}{2\pi}\int_{0}^{2\pi}\int_{25^{\circ}}^{90^{\circ}} d\Omega = \frac{1}{2\pi}\int_{0}^{2\pi}\int_{25^{\circ}}^{90^{\circ}} \sin\theta\, d\theta\, d\phi = \frac{1}{2\pi}(2\pi)\left(-\cos\theta \Big|_{25^{\circ}}^{90^{\circ}}\right)$$

$$= -(0 - 0.906 \cong 91 \text{ percent} \qquad (14)$$

This analysis excludes the effects of the space vehicle and the solar array which were considered negligible.

CONCLUDING REMARKS

The SERT II communications system has performed well to date with no failures. One anomaly was observed upon solar panel deployment. The fluctuations in the housekeeping array voltage caused the time code generator to count erratically and read 249 days. After the initial anomaly, the time code generator counted properly, and on February 9, 1970 was reset to zero and has counted properly since.

The STADAN stations have been able to acquire the spacecraft telemetry nearly at the horizon and the maximum signal strength received from the spacecraft was -86 dBm. These observations confirm the link calculations.

A characteristic of the ion thruster system, as utilized for the SERT II mission, is that it arcs occasionally. Arcing can induce a transient on the telemetry lines of up to 400 volts peak with a time to first peak of approximately 200 nanoseconds. During ground testing the input gates of these subcommutators were damaged by these transients. To protect the subcommutator input gates from this transient, a filter box was installed on the spacecraft. Future spacecraft should also provide protection for the input gates, either separately or internally. In addition, these transients caused loss of synchronization of the subcommutators in ground testing during engine startup. For additional protection all of the telemetry equipment should be contained in one box to provide additional isolation, and all wiring should be shielded.

As of June 30, 1970, 2873 commands have been transmitted to the spacecraft. Of these, 34 were not verified and were retransmitted. Three of the commands were verified and executed, but the spacecraft did not respond. One of those was probably due to late timing of the enable tone which was preceded by the automatic clear of the decoder.

The reason for the lack of response of the other two commands is unknown. Of the total commands transmitted, 1.18 percent were not verified correctly and were retransmitted. The percentage of the total commands transmitted attributable to the nonresponsive command is 0.104 percent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 21, 1970,
704-13.

REFERENCE

1. Jasik, Henry, ed.: Antenna Engineering Handbook. McGraw-Hill Book Co., Inc., 1961, pp. 3-5.

TABLE I. - EQUIPMENT ERROR CHARACTERISTICS

Source	Subcommutator limits	Worst case error signal, mV
Input impedance	>50 MΩ	0.5
Back current	0.3 μA	1.5
Gain (K = 1)	+0 percent, -0.05 percent	2.5
Offset	±2 mV	2.0
Scatter	±500 μV	.5
Crosstalk	0.1 percent	5.0
Linearity	±0.05 percent	2.5
Internal noise	±2 mV	2.0
Output impedance	4.7 kΩ into 10 kΩ	.5

Source	Multicoder limits	Worst case error signal, mV
Input impedance	>50 MΩ	-----
Back current	0.3 μA	0.006
Gain (K = 1)	+0 percent, -0.05 percent	2.5
Offset	±2 mV	2.0
Scatter	±500 V	.5
Crosstalk	0.1 percent	5.0
Linearity	±0.05 percent	2.5
Internal noise	±2 mV	2.0
Quantizing	0.4 percent ±41 mV	61.0

Data link bit error rate	
Real time data	1 bit in 10^6
Playback data	1 bit in 10^5

Ground data handling equipment digital to analog converter		Worst case error signal, mV
Full-scale error	Adjustable to zero	-----
Zero-scale error	Adjustable to zero	-----
Linearity	±0.1 percent of best straight line	3.75

TABLE II. - WORST CASE ERROR

Error source	Error signal, mV
Subcommutator back current	1.5
Subcommutator nonunity gain	2.5
Subcommutator offset	2.0
Subcommutator scatter	.5
Subcommutator crosstalk	5.0
Subcommutator linearity	2.5
Subcommutator internal noise	2.0
Nonzero data output impedance	.5
Multicoder back current	.006
Multicoder nonunity gain	2.5
Multicoder offset	2.0
Multicoder scatter	.5
Multicoder crosstalk	5.0
Multicoder linearity	2.5
Multicoder internal noise	2.0
Nonzero subcommutator output impedance	.47
Analog to digital quantizing error	61.0
Digital to analog linearity error	5.0
Total[a]	97.5

[a] Total error corresponds to 1.95 percent of 5-V full-scale signal.

TABLE III. - RADIOFREQUENCY POWER BUDGET

[Calculations are for maximum slant range of 3600 km.]

(a) Downlink

	Verification	Stored data	Real time	Tracking
Nominal frequency, MHz	137	137	137	137
Transmitter power (350 mW), dBw	-4.6	-4.6	-4.6	-4.6
Transmitter antenna gain, dB	-7.0	-7.0	-7.0	-7.0
Space loss (3600 km), dB	146.3	146.3	146.3	146.3
Receiving antenna gain, dB	22	22	22	16.0
Losses, dB	2.0	2.0	2.0	5.0
Channel power fraction, dB	-16.1	-9.5	-4.9	-4.6
Channel signal level, dBw	-154.0	-147.4	-142.8	-151.5
Channel noise level, dBw	-176.2	-166.3	-170.0	-188.7
SNR, dB	21.2	18.9	27.2	37.2
Threshold, dB	13	13	13	35.2
Margin, dB	8.2	5.9	14.2	2.0

(b) Uplink

Nominal frequency, MHz	149
Transmitter power (200 W), dBw	23
Transmitter antenna gain, dB	10
Space loss (3600 km), dB	147.0
Receiving antenna gain, dB	-7
Losses, dB	7.5
Polarization loss, dB	3
Receiver signal level, dBw	-131.5
Noise level, dBw	-149.6
SNR, dB	18.1
Threshold, dB	10
Margin, dB	8.1

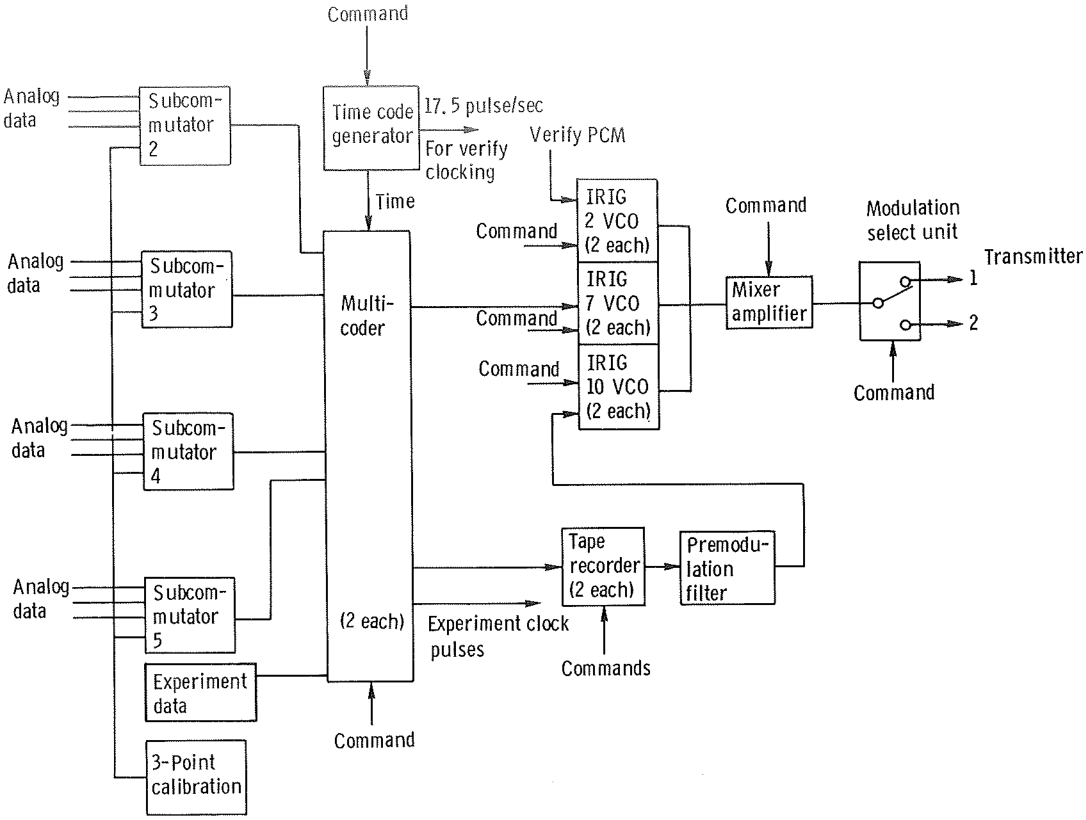

Figure 1. - Telemetry system block diagram.

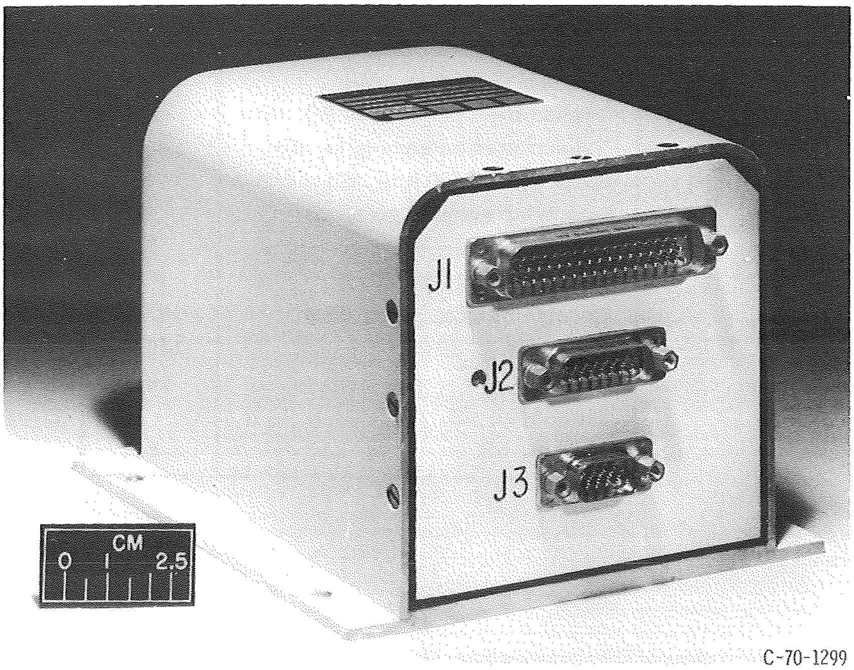

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Figure 2. - Multicoder.

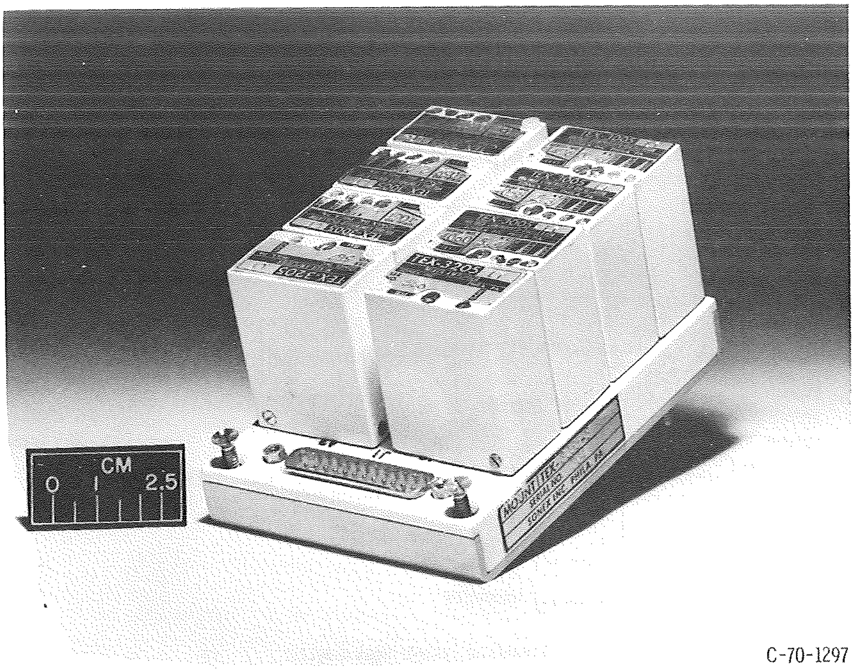

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Figure 3. - Frequency division multiplex assembly.

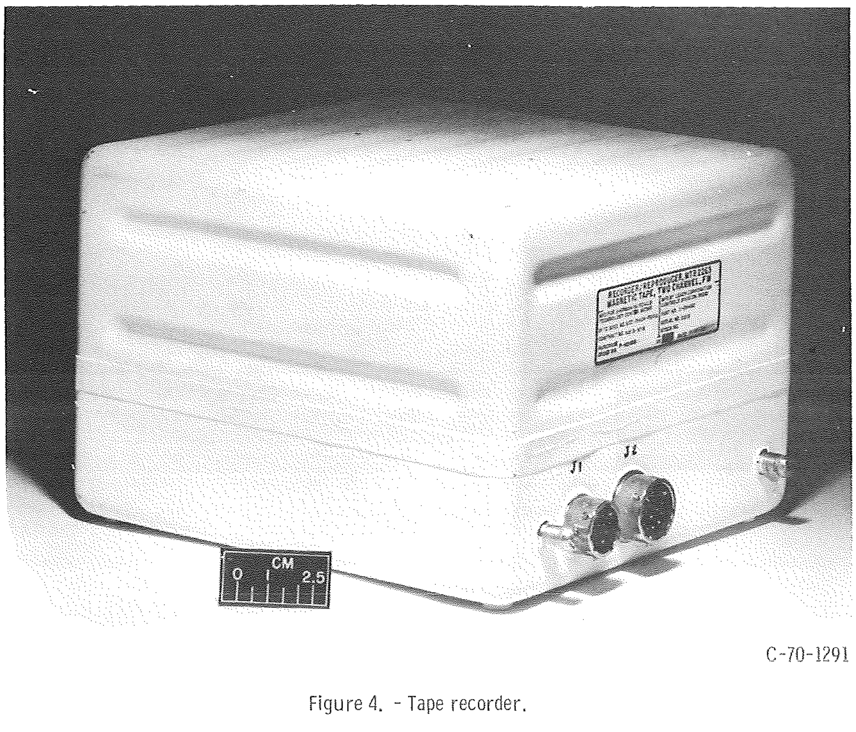

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Figure 4. - Tape recorder.

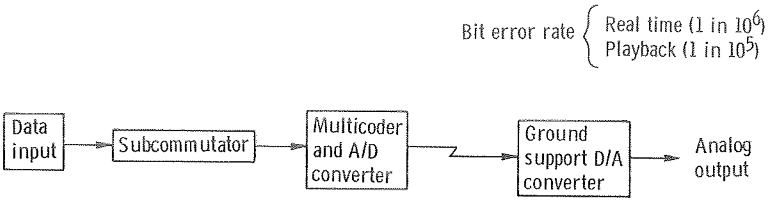


Figure 5. - System error block diagram.

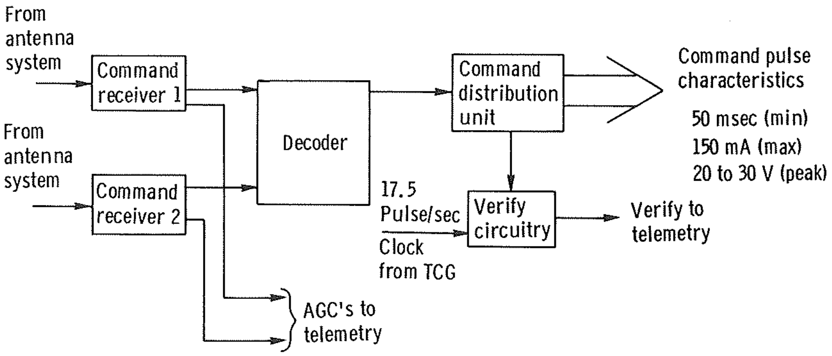


Figure 6. - Command system block diagram.

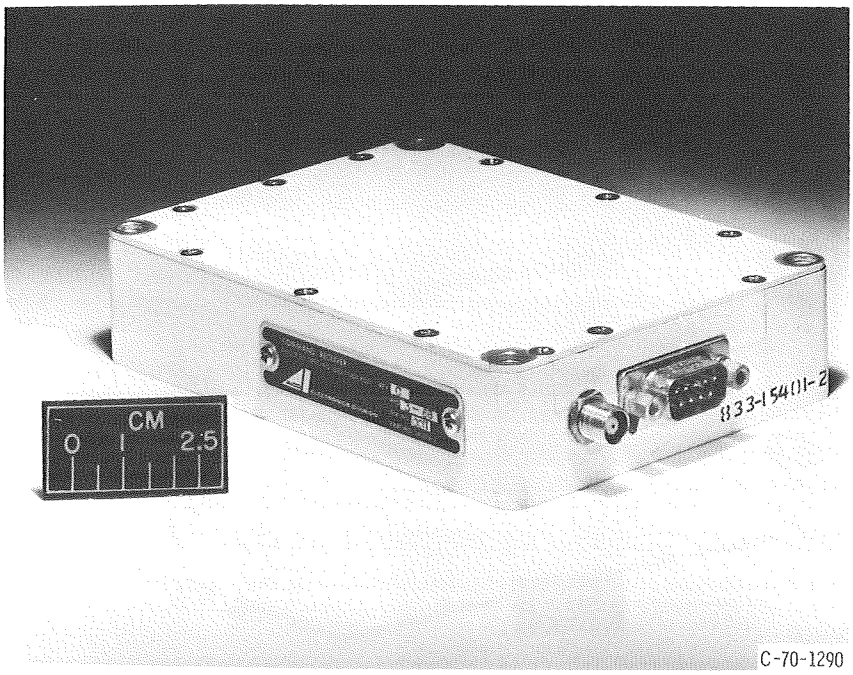


Figure 7. - Command receiver.

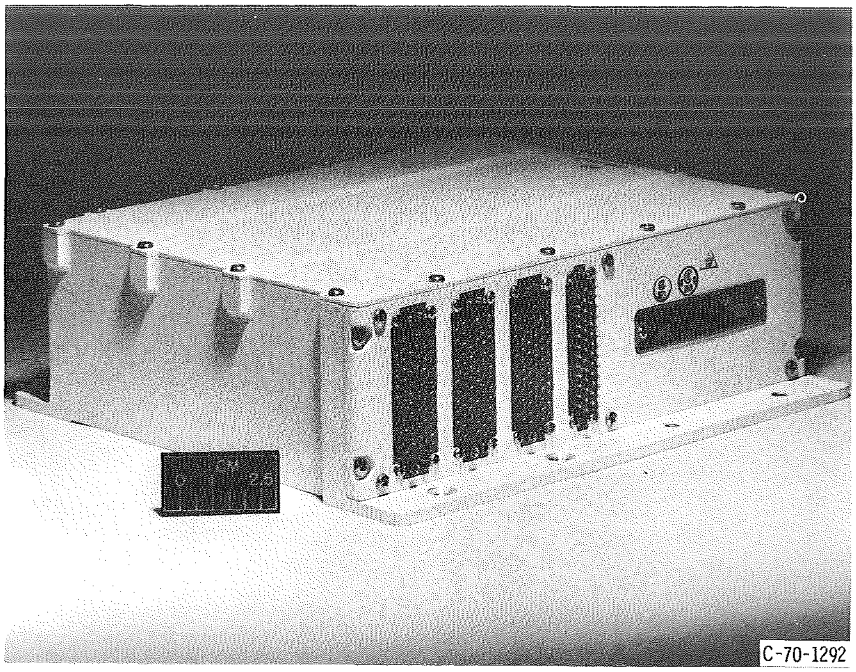
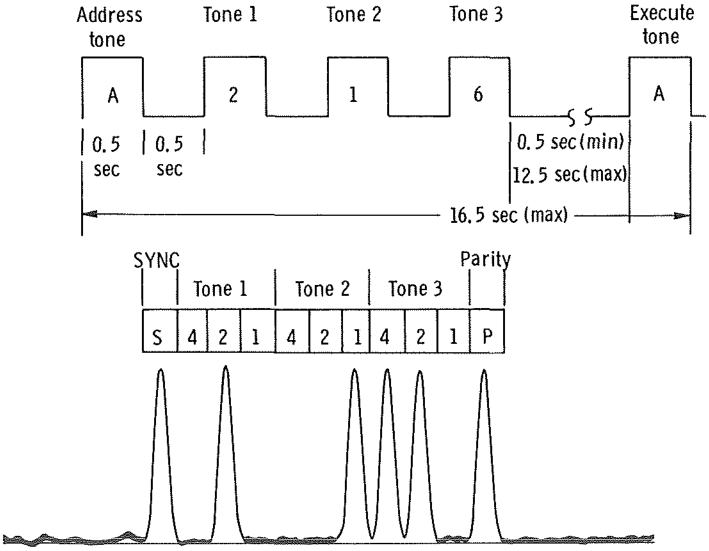


Figure 8. - Command decoder.



Verify of command 216

Figure 9. - Command and verify format.

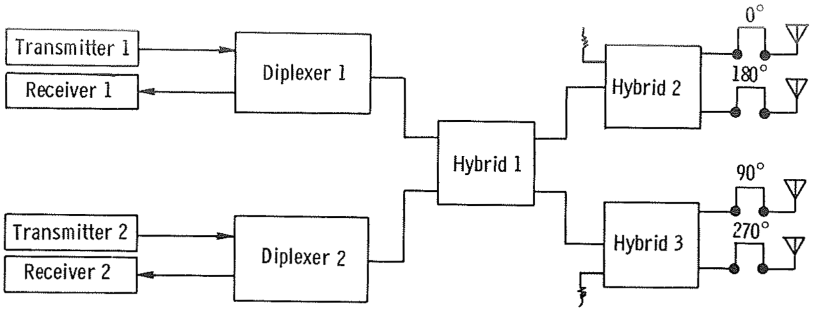


Figure 10. - Radiofrequency system block diagram.

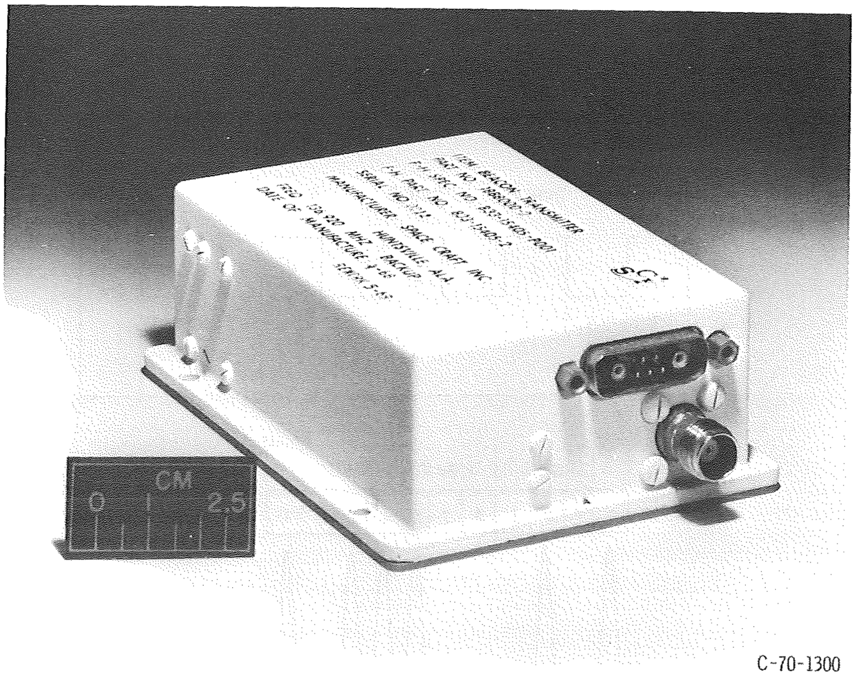


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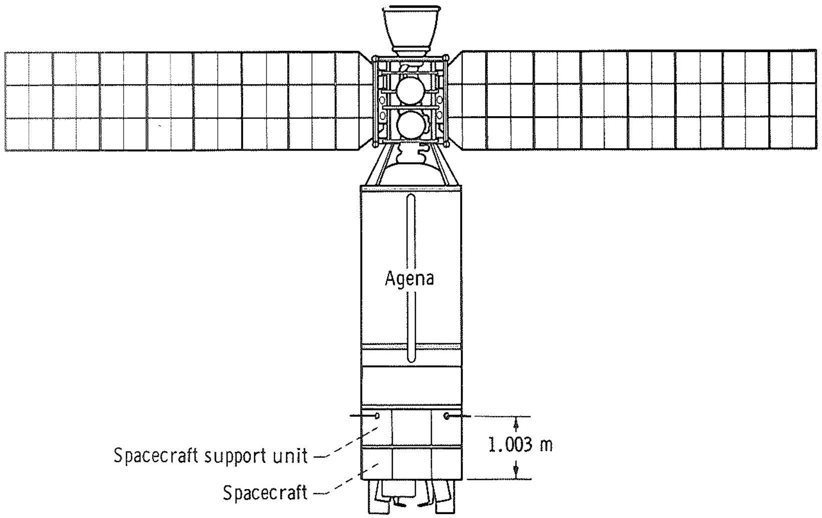
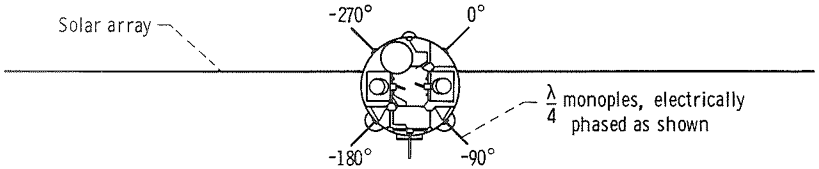
Figure 11. - Telemetry transmitter.



(a) Side view.



(b) Bottom view.

Figure 13. - Sert II antenna configuration.

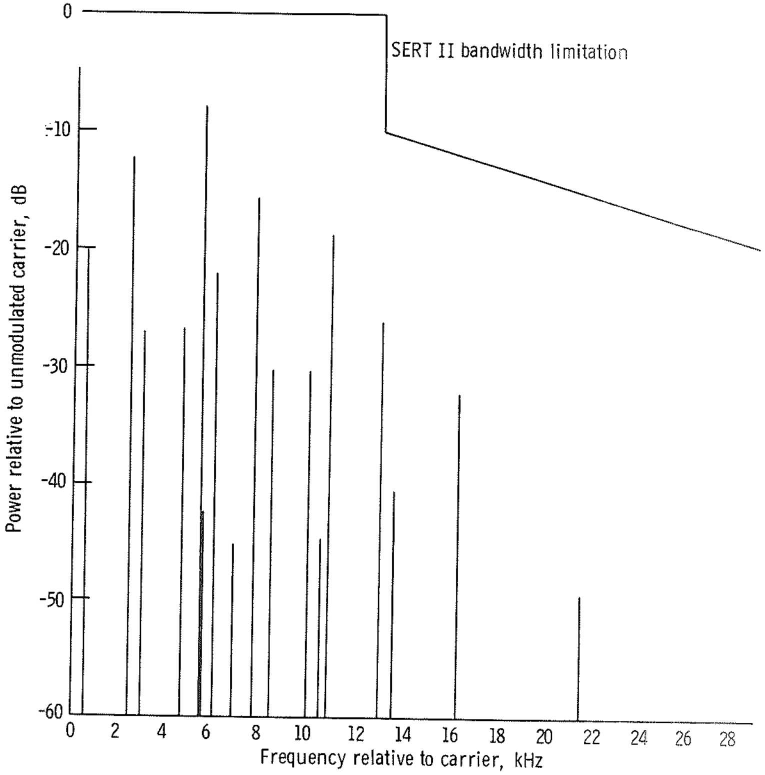


Figure 12. - SERT II radiofrequency spectrum.

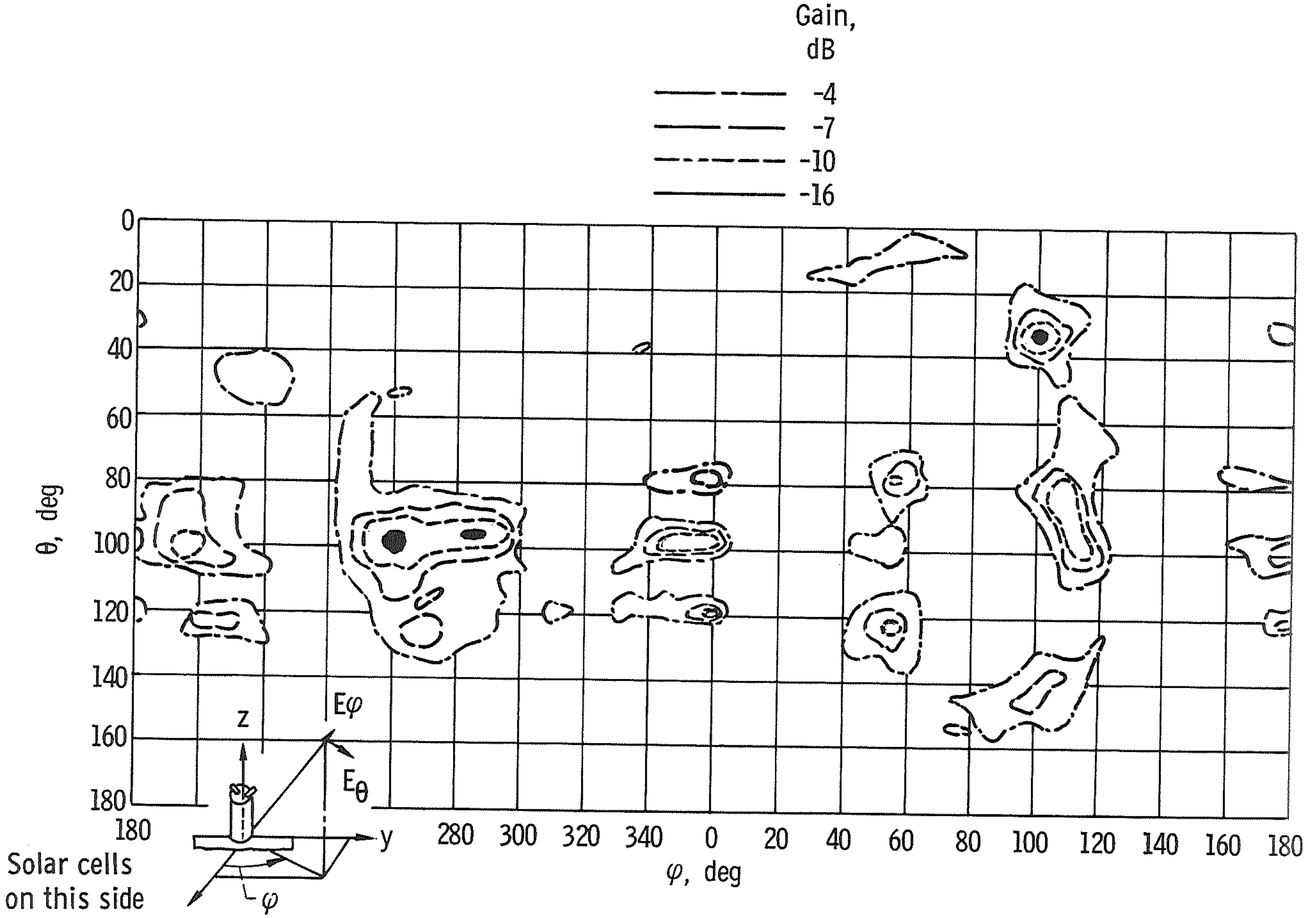


Figure 14. - Antenna system coverage. Frequency, 1420 megahertz; one-tenth scale model of SERT II/Agena spacecraft; λ/4 monopoles (turnstile feeding); gain referenced to isotropic.

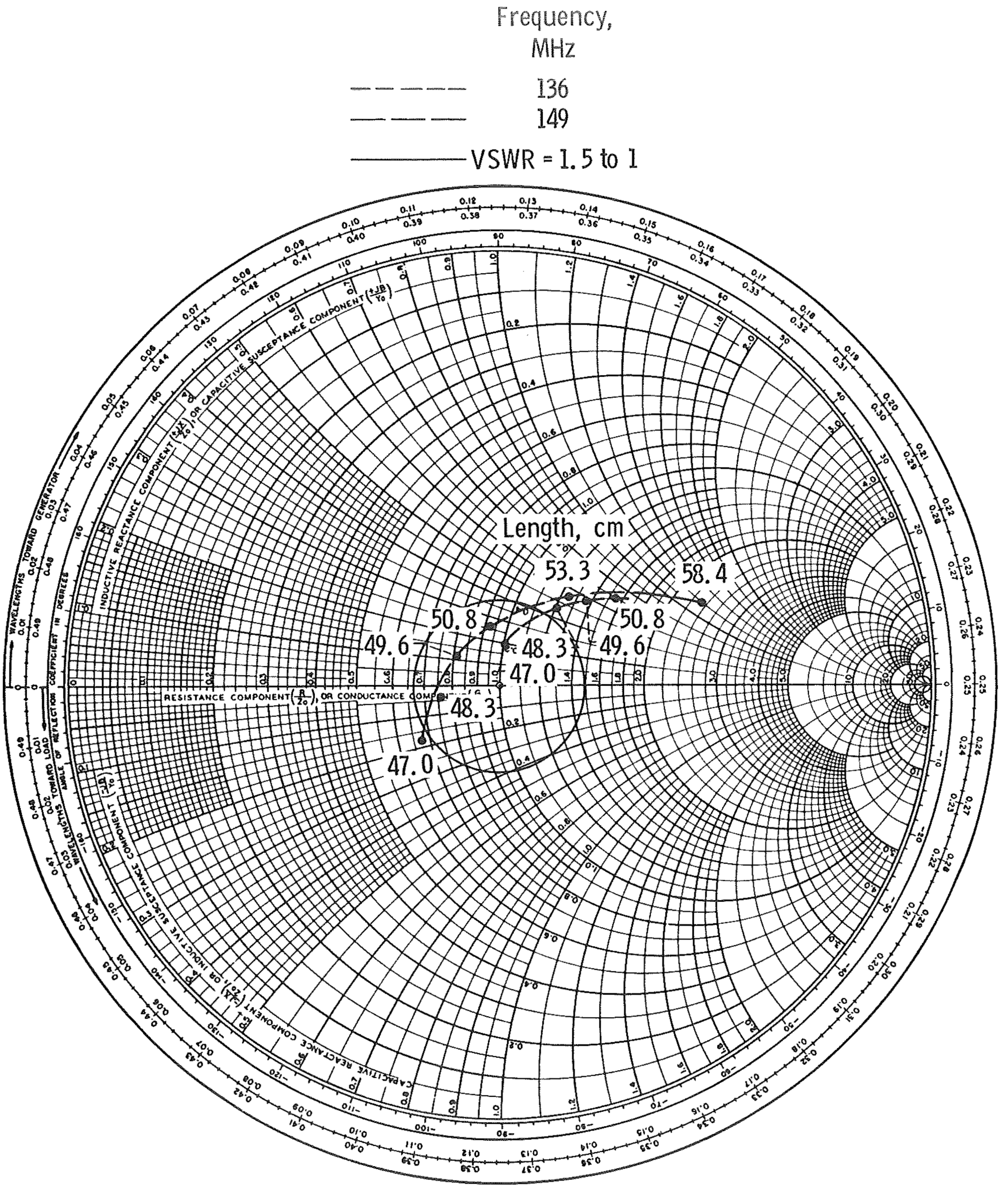


Figure 15. - SERT II monopole impedance plotted against length.

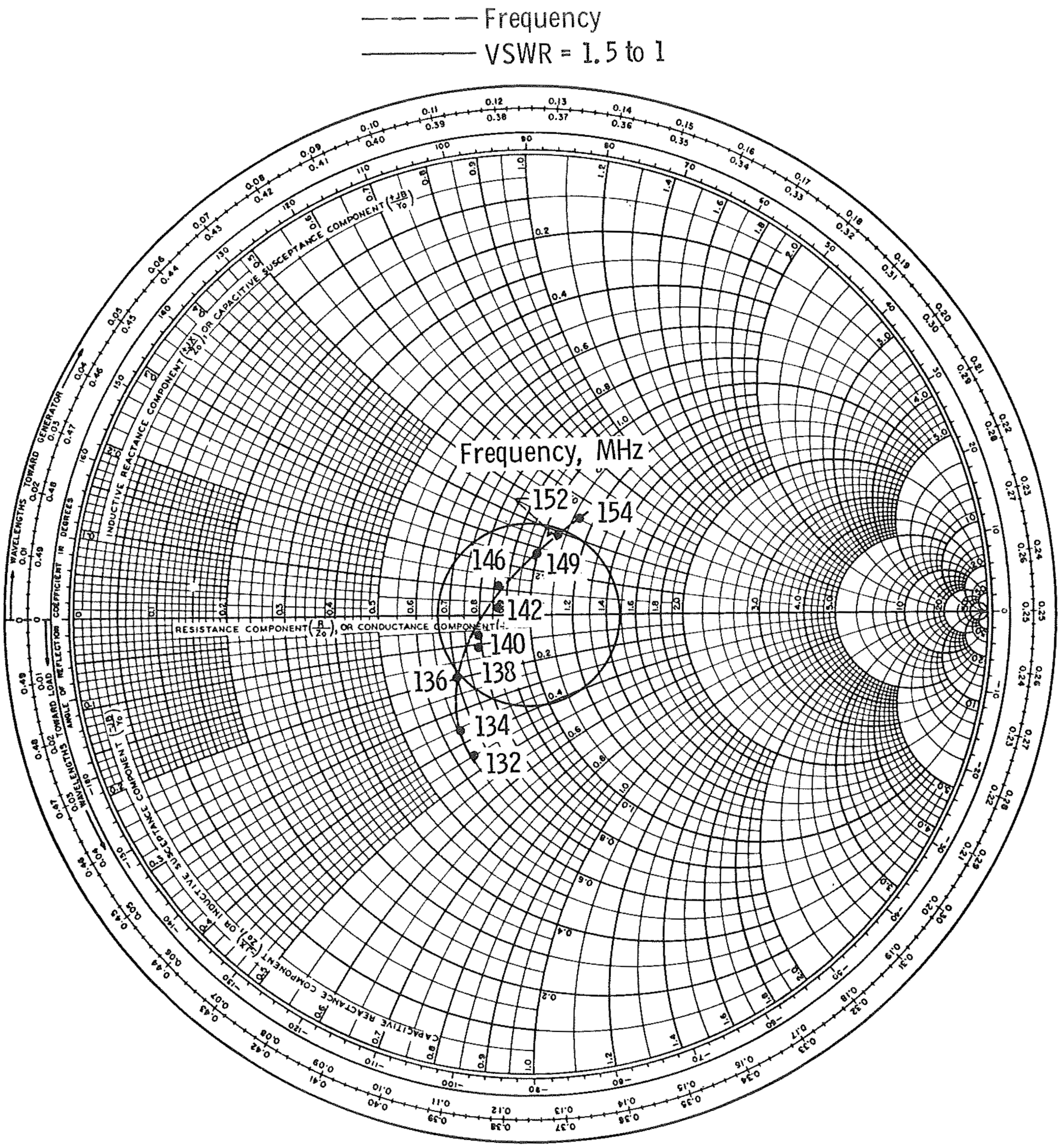


Figure 16. - SERT II monopole impedance. Diameter, 5/16 inch (0.793 cm); length, 18.8 inches (47.8 cm).

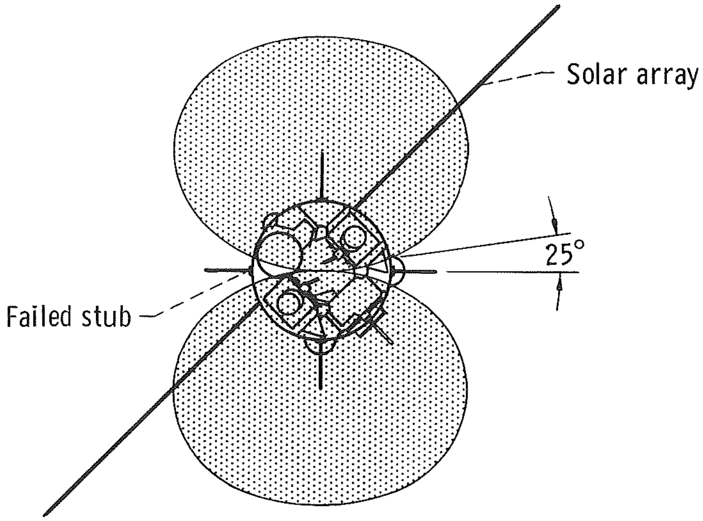


Figure 17. - Dipole pattern coverage.

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