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SKYLAB VECTORCARDIOGRAPH: SYSTEM DESCRIPTION AND IN-FLIGHT OPERATION

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16. Abstract

A vectorcardiograph system was used to measure cardiac electrical activity of Skylab crewmen. This system was chosen because of its data-quantification advantages. The vectorcardiograph was required to meet recommended American Heart Association specifications, to withstand space environmental extremes, and to facilitate data gathering in the weightless environment. The vectorcardiograph system performed without failure, and all projected data were acquired. The appendix lists the design specifications used for the Skylab vectorcardiograph system.

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SUMMARY

A system for quantitating the cardiac electrical activity of Skylab crewmen was required for several medical experiments designed to evaluate the effects of space flight on the human cardiovascular system. A vectorcardiograph system was chosen for this task because of its data-quantification capabilities. To be used effectively in space flight, however, the system had to meet certain other requirements.

1. The system was required to meet the specifications recommended by the American Heart Association.

2. The vectorcardiograph had to withstand the extreme conditions of the space environment.

3. The system had to provide features that permitted ease of use in the orbital environment.

The vectorcardiograph system developed for this application is discussed in this report with special emphasis on the three requirements.

INTRODUCTION

During the earlier space programs - Mercury, Gemini, and Apollo - the activity of crewmen's hearts was monitored by using an electrocardiograph (ECG). Such monitoring was a necessary crew safety precaution to provide early detection of any physiological anomaly that might require the expeditious return of a crewman to Earth. After the longer duration space missions (some lasted as long as 14 days), the crewmen's cardiovascular systems exhibited distinct changes. After having adapted to the weightless condition, the cardiovascular system apparently had developed less tolerance for the one-g environment on return from space. The approaching Skylab missions, with expected durations of 2 months, would require a means of measuring the time course of cardiovascular changes during flight. This information could be used to help determine countermeasures if physiological anomalies occurred on longer missions. Experiment protocols included cardiac

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monitoring during periods of controlled exercise and orthostatic stress. Each crewman was to be monitored approximately every third day in flight.

A vectorcardiograph (VCG) system was selected for cardiac monitoring of Skylab crewmen because it allowed the following.

1. Determination of quantitative changes of heart electrical activity

2. Near-real-time monitoring of heart activity in the conventional manner because the VCG output could be converted on the ground to the standard 12-lead ECG output (ref. 1)

3. 75-percent reduction in the amount of data required for analysis because only 3 leads are involved instead of the usual 12

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

DESIGN CONSIDERATIONS

The VCG system to be developed for the Skylab Program had to be as up to date as any currently on the market; that is, parameters such as phase matching between channels, system noise, and common mode rejection had to be within the ranges recommended by the American Heart Association (AHA) (ref. 2). The appendix lists the Skylab VCG performance specifications and the applicable paragraphs of the AHA recommendations so that a detailed comparison can be made. In addition to being the best available system, the VCG had to be constructed to survive the rigors of the launch environment and to operate properly in weightlessness and in the reduced atmospheric pressure of the Skylab.

Several unique features were designed into the system to facilitate operation in space, to protect the crewmen during operation of the VCG, and to protect the VCG during use. An electroshock protection (ESP) system was provided to preclude electrical shock to the crewman/subject if a failure occurred in the VCG system. For additional protection, an isolation measurement system was provided that determined the electrical isolation of the subject from structure ground. Using this system to verify isolation greater than 1 megohm, the subject would have the same protection as that provided by the ESP if he contacted a current source outside the VCG.

To protect the VCG system inputs, an electrostatic discharge protection system was provided. Tests had shown that, in the Skylab environment, a subject could build up a body surface charge of as many as 3000 volts. It was reasonable to assume that this accumulated charge could be instantaneously discharged into the VCG inputs, for example, when the subject first connected himself to the system. Thus, the Skylab VCG was designed to withstand an instantaneous discharge directly into VCG inputs from a subject charged to 3000 volts.

A system was provided that determined the subject's heart rate from the VCG output. This measurement was telemetered to the ground and was simultaneously displayed in the Skylab as one of the key parameters used to monitor the condition of the subject during a biomedical experiment.

The high input impedance of the VCG system permitted relatively high (approximately 100 kilohms) electrode-to-skin impedance. With the electrode system used, electrode contact impedance was consistently below this value, with minimal skin preparation. The value of electrode-to-skin impedance for each electrode was checked before an experiment run with the electrode check system so that an electrode that did not meet the 100-kilohm requirement could be detected and replaced.

Two highly convenient features were the automatic output bias control and the automatic transient recovery circuits. The bias control circuit maintained the baseline of the output signal automatically at a predetermined level even during periods of exercise by the subject, thereby freeing the observer for other tasks. Similarly, if a transient voltage occurred at the inputs and caused the output voltage to go off scale, the transient recovery circuit would return the output signal to the baseline condition without any effort on the part of the observer. In conventional VCG's, these two circuits are initiated manually by a reset button.

SYSTEM DESCRIPTION

The major hardware components of the Skylab VCG system, shown in figure 1, include an electrode harness, a subject interface box (SIB), an electrical umbilical, and an electronics module. The electrode harness consists of the eight electrodes (seven active and one ground reference) necessary for Frank resistor network summing, interconnecting wiring, and connectors. The electrical potentials on the subject's skin were detected by the electrodes placed on the upper part of the torso. Figure 2 shows the electrode placement and designation. The right sacrum (RS) electrode served as the reference. For convenience, four colors of electrical insulation were used in the harness, one color for each pair of electrodes. The RS and left sacrum (LS) electrodes used green wire; the right axilla (RA) and front (F) electrodes used red wire; the left axilla (LA) and left chest (LC) electrodes used orange wire; and the back (B) and neck (N) electrodes used yellow wires. The electrodes (fig. 3) were silver/silver chloride pressed pellets bound by epoxy to a Plexiglas housing to a depth of 1.27 millimeters (0.050 inch). To provide the electrical contact between the electrodes and the skin, electrolyte-saturated sponge disks were placed in the well of each electrode. Double adhesive tape rings were used to attach the electrodes to the skin.

A VCG electrode kit (fig. 4) contained 6 harnesses (2 per crewman), a roll of 640 attachment tapes, 80 packages of sponges (8 sponges per package), and wet wipes for skin preparation and electrode cleansing. The wet wipes and sponges were packaged at 3447 N/m^2 (0.5 psia) to preclude ballooning with consequent rupturing of seals at the low pressure that existed in the Skylab between manned missions. The container used to stow these items was a reinforced Beta cloth bag. Fully packed, the kit measured 15 by 15 by 20 centimeters (6 by 6 by 8 inches) and weighed 3.2 kilograms (7 pounds).

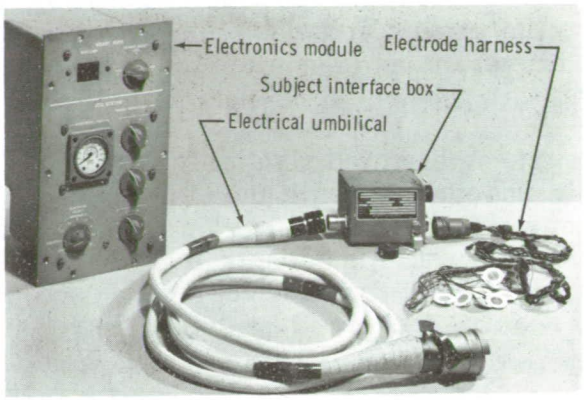


Figure 1.- Skylab vectorcardiograph system.

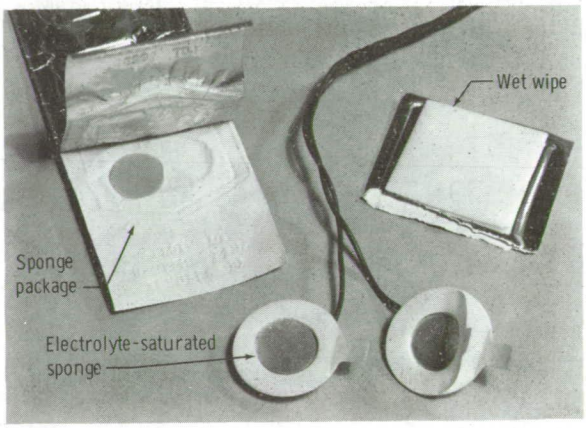
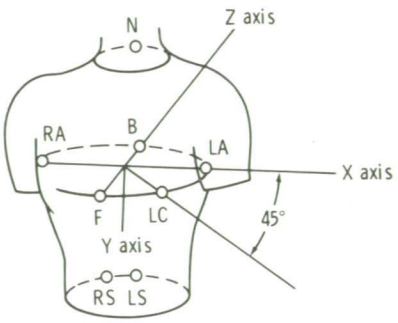


Figure 3.- Electrode configuration.



Explanation

Frank system designation	Anatomical designation	Anatomical location
E	F	Front
C	LC	Left chest
A	LA	Left axilla
M	B	Back
I	RA	Right axilla
H	N	Neck
G	RS	Right sacrum
F	LS	Left sacrum

Figure 2.- Electrode placement on subject's torso.

The major functional components of the VCG system located in the SIB and in the electronics module are shown in figure 5. The SIB provides, in series with each electrode lead, electrostatic discharge protection, electroshock protection circuitry, and, except for RS, a preamplifier. Figure 6 is a detailed schematic of these features for a typical electrode lead. The heart's electrical signal enters the SIB through pin 9 and passes through the ESP circuit into preamplifier A_1 and finally to the electronics module through pin 5. The unity-gain preamplifier provides impedance buffering between the high input impedance from the body and the low-impedance Frank resistor network.

If the subject contacts a dangerous electrical source outside the VCG or if a dangerous electrical source is generated by a failure within the VCG, the electroshock protection circuitry in each lead will limit the current through the body to less than 200 microamperes for source voltages as high as 200 volts peak and frequencies from direct current to 1 kilohertz. Field-effect transistors Q_1 and Q_2 limit the current if the signal is positive, and Q_3 and Q_4 if it is negative. In normal operation, these field-effect transistors are in their maximum conduction state. Resistor R_3 and diode array CR_5 provide the input with electrostatic discharge protection. For input voltages greater than 215 volts peak, CR_5 clamps to ground, bypassing and thus protecting the normal input.

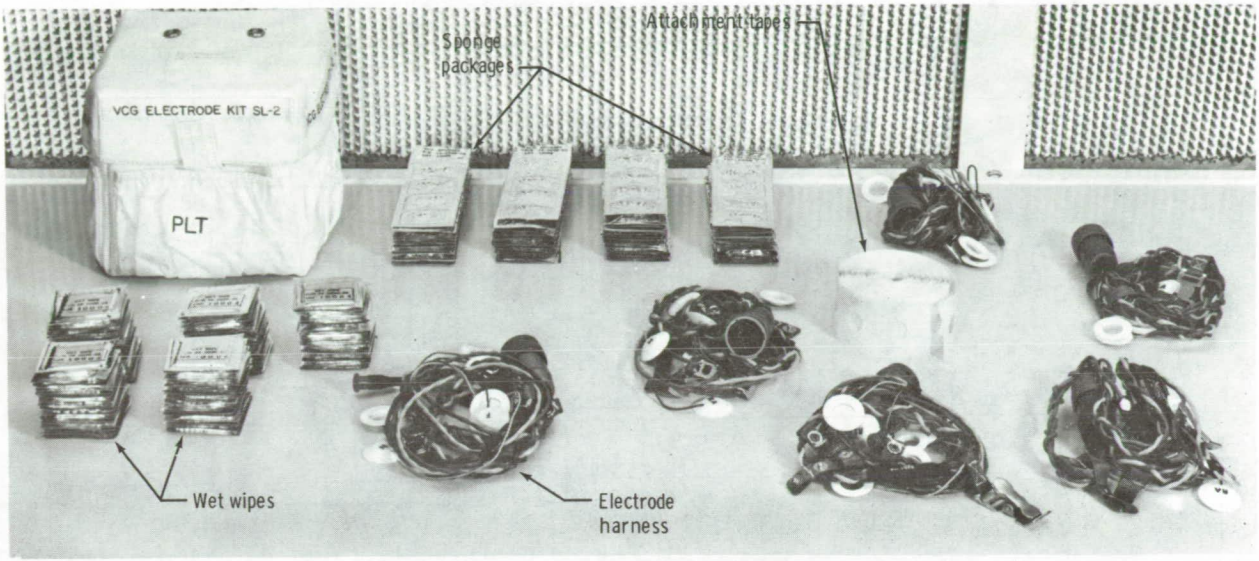


Figure 4.- Electrode kit components.

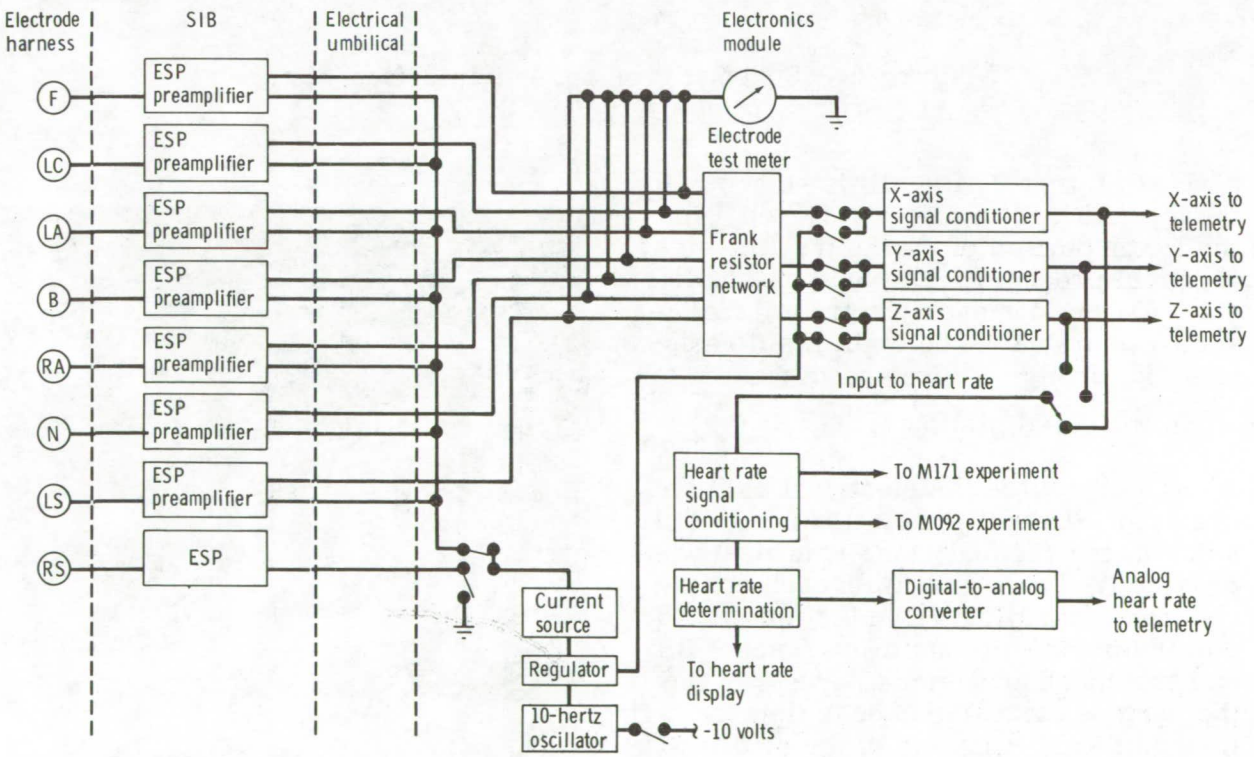


Figure 5.- Functional diagram of VCG.

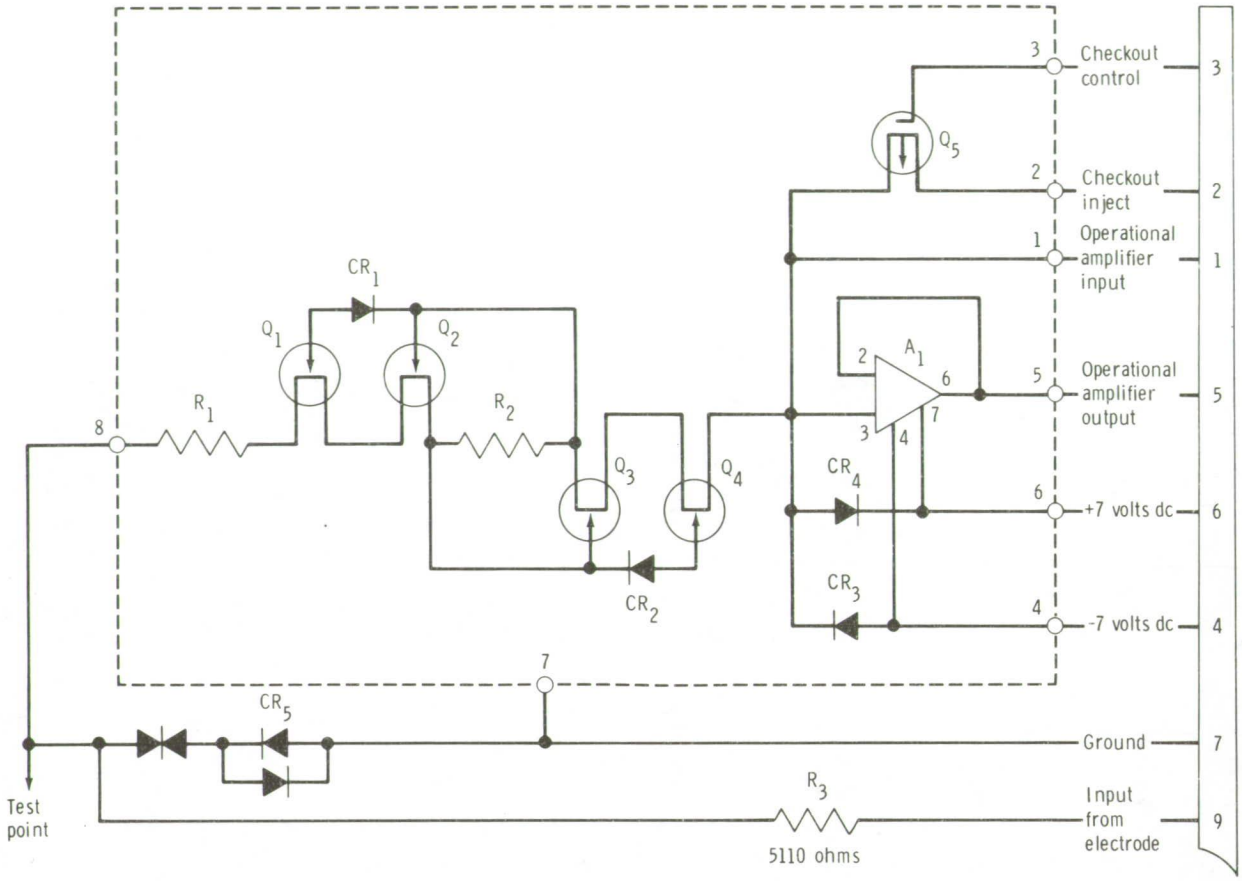


Figure 6.- Schematic of subject interface box.

In figure 7, the SIB is shown with the top and bottom plates removed. In the lower portion of the figure, the eight identical preamplifier hybrid assemblies (fig. 6), one for each electrode, are shown installed. The eight input resistors (R_3 in fig. 6) are shown mounted on an insulated platform.

To provide the electrical path between the SIB and the electronics module, a 3.3-meter (11 foot) long umbilical was provided. The signal from each active electrode, the plus-7- and minus-7-V dc power for each preamplifier (except RS), and the checkout signals necessary for the various electrode checks flow through the umbilical. One end of the umbilical is mated to the SIB; the other end, with a

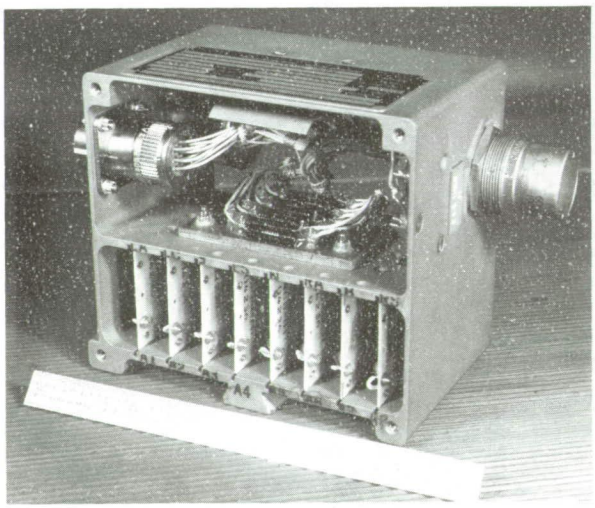


Figure 7.- The subject interface box.

zero-g connector, is connected to an experiment support system (ESS) in which the electronics module was installed.

The electronics module (fig. 8), which weighs approximately 5 kilograms (11 pounds) and measures 29 by 15 by 20 centimeters (11.5 by 6 by 8 inches), is the core of the VCG system. The Frank resistor network, the VCG signal conditioners, the control circuitry for the electrode checks, the calibration circuitry, and the heart rate determination and display circuitry are located in the electronics module. These features will be discussed in turn, and the system functional diagram (fig. 5) can be referred to for orientation.

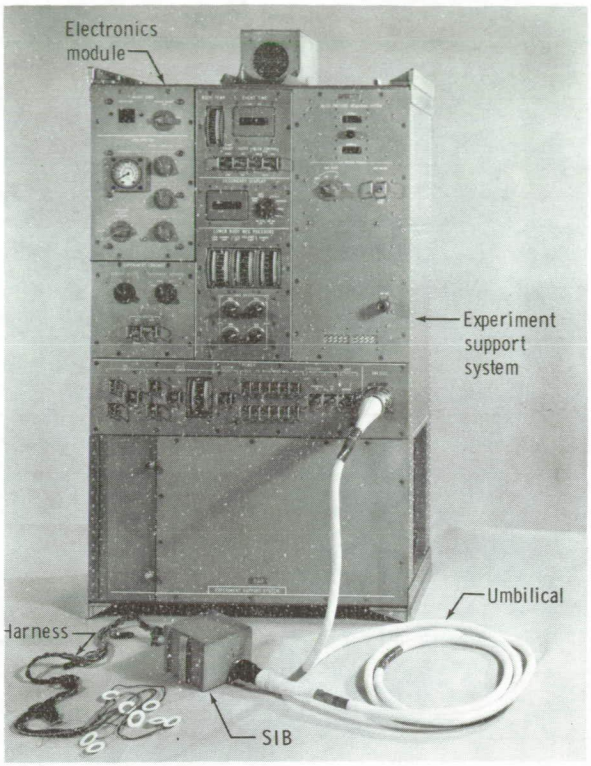


Figure 8.- Electronics module installed in experiment support system.

Frank Resistor Network

The standard Frank resistor network (ref. 3) is used for the VCG system, and the value of each resistor is set at 10 kilohms. The network schematic is shown in figure 9. Electrical signals from each of the seven active electrodes are combined in the network to produce the X, Y, and Z leads of the VCG. There are three identical signal conditioners, one for each axis; each of the three outputs of the Frank network is routed to a signal conditioner.

Signal Conditioner

Three identical signal conditioners provide waveform shaping, noise rejection, amplification, and transient recovery circuits. A schematic is shown in figure 10. The first stage is a differential amplifier having a fixed gain of 15.6. Output from the first stage flows into a second-stage differential amplifier with a fixed gain of 48. Both the first two stages are designed so that input signals with a frequency of 50 kilohertz or greater pass through with a gain of 1. The second-stage output flows into the third stage, a single-ended differential amplifier having a gain of 1. This stage incorporates the first pole of a three-pole active Butterworth low-pass filter and provides approximately 50 decibels of 50-kilohertz attenuation. The signal next goes into the fourth stage, the variable-gain stage, which has six selectable gain factors ranging from 1 to 3.75. The output of this stage flows into the fifth and last stage, which provides the other two poles of the Butterworth low-pass filter. An additional 100 decibels of 50-kilohertz attenuation is provided by this stage. Low-frequency bandpass shaping is performed by the coupling capacitors between the first two stages. High-frequency bandpass shaping is performed by the last three stages and the associated passive elements.

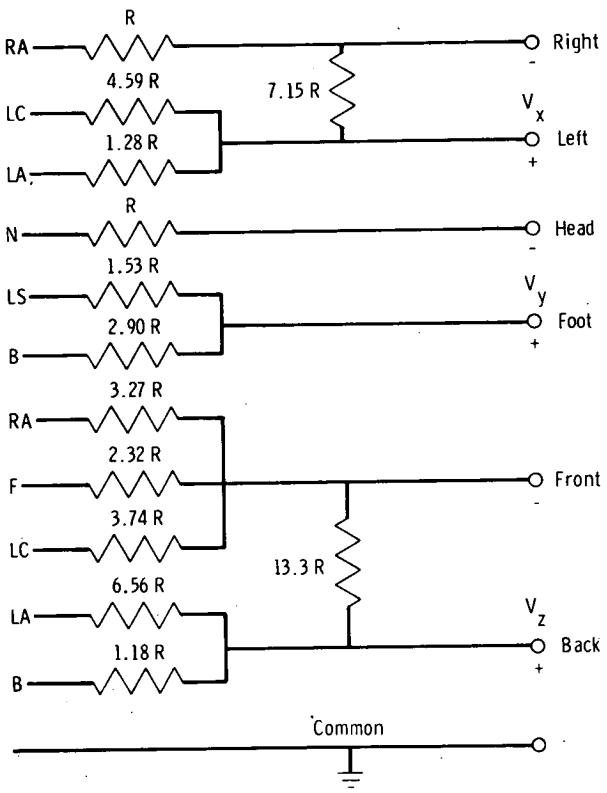


Figure 9.- Frank resistor network.

The automatic transient recovery circuit senses at the output when an excessive signal has been applied to the inputs. In this condition, the output of the first stage is clamped to ground and bypasses the remainder of the signal conditioners. When the voltage detector senses that the output voltage has returned to a value in the nominal 0- to 5-volt range, the ground is lifted and signal flow returns to normal. Recovery time is nominally 5 seconds. The output signal is also sensed by the automatic biasing circuit and fed back to the inputs of the third and fourth stages to maintain the output of the signal conditioner at a nominal plus 1.7 V dc. The analog output from the three signal conditioners is then ready for routing to telemetry with one channel (selectable) also being routed to the heart rate determination and display system.

Heart Rate Circuit

Selection of the channel to be routed to the heart rate system is made with

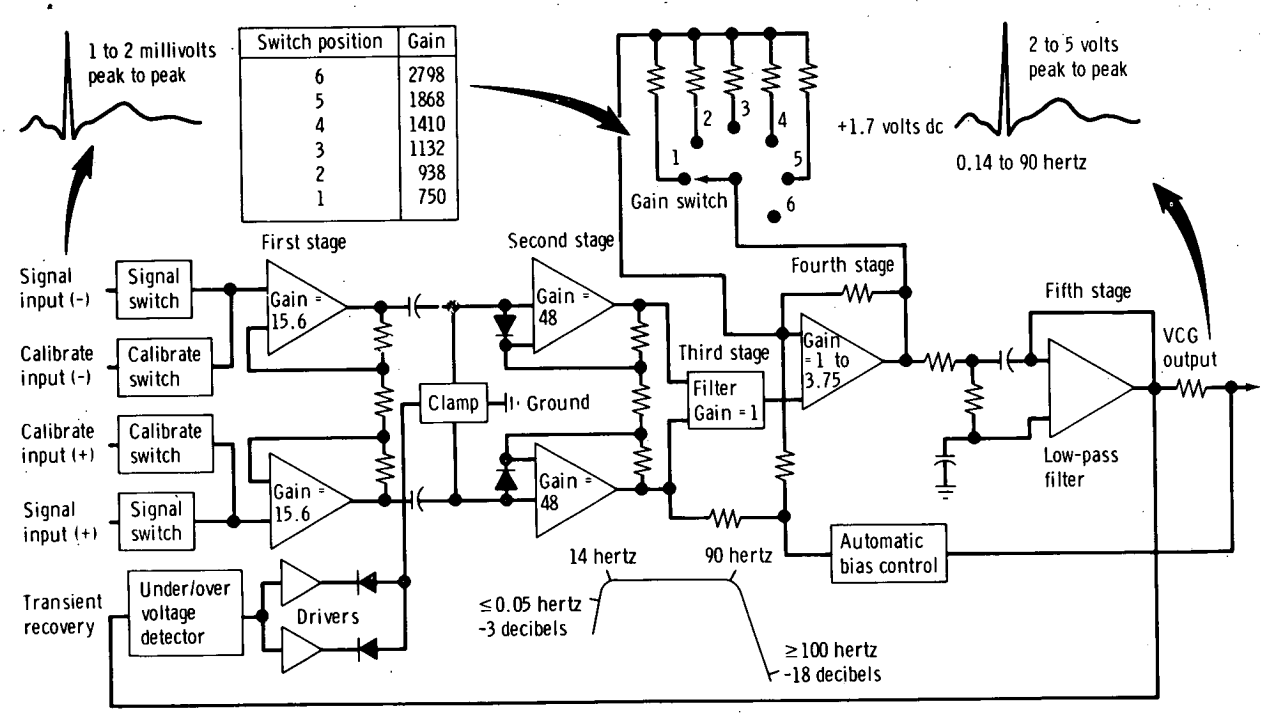


Figure 10.- Schematic of signal conditioning.

the "source select" switch on the front panel of the module. The selected signal is first filtered to remove noise and artifacts, full wave rectified, then amplified so that the largest peaks lie between 4.5 and 5 volts. The conditioned signal next flows to circuitry for determination as to whether the signal is a legitimate heartbeat. This determination is accomplished as follows.

1. A pulse is generated when the signal level exceeds 2.5 volts. The pulse width corresponds to the length of time the signal level is above 2.5 volts.

2. Another pulse is generated at the same time a peak occurs. The leading edge is formed at the instant the peak occurs, the falling edge at the instant the signal level falls below 2.5 volts.

3. The two pulses are compared. If the peak occurs between 3 and 63 milliseconds after the level exceeds 2.5 volts, the signal is recognized as a legitimate heartbeat, and a square-wave pulse corresponding to that heartbeat is produced.

The square wave pulses are routed to the heartbeat counter, the first stage of the heart rate computation and display. The heart rate computation procedure is as follows.

1. A synthesizer/counter is preloaded with the number 348 as the heartbeat counter begins to count pulses.

2. The synthesizer/counter decrements until the heartbeat counter has counted five pulses.

3. A holding register copies synthesizer/counter value and drives a digital display and a digital-to-analog converter. The synthesizer/counter value, which is the heart rate in beats per minute (bpm) averaged over five heartbeats, is numerically displayed on the module front panel and provided to telemetry as an analog signal in the range 0 to 5 volts.

4. The synthesizer/counter is reset to 348, and computation of the heart rate for the next five heartbeats begins. The display and the analog value are updated after each computation for five heartbeats.

The synthesizer/counter computation is based on the formula

$$\text{Heart rate (bpm)} = \frac{(5 \text{ pulses}) \left(60 \frac{\text{seconds}}{\text{minute}}\right)}{T \text{ (seconds)}} \qquad (1)$$

where T is the period for five heartbeats. The heart rate measuring system, to approximate this formula, uses the algorithm

$$\text{Heart rate (bpm)} = 348 - T_m f_m \qquad (2)$$

where T_m is the time duration at frequency f_m. A pulse generator operating from a 4-kilohertz oscillator provides the selected frequencies. Specifically, the heart rate (bpm) is $348 - (T_1f_1 + T_2f_2 + T_3f_3 + T_4f_4 + T_5f_5 + T_6f_6 + T_7f_7)$

Values for T_m and f_m are given in table I.

TABLE I.- HEART RATE SYSTEM COMPUTATION SEQUENCE

m	Time (T_m), sec	Frequency (f_m), Hz	Synthesizer/counter value	
			Start	End
1	2.000 ± 0.005	100	348	148
2	.280 ± .005	50	148	135
3	.030 ± .005	100	135	132
4	.640 ± .010	50	132	103
5	1.120 ± .20	25	103	75
6	1.840 ± .040	12.5	75	52
7	1.760 ± .080	6.25	52	40

The synthesizer/counter decrements using 200 pulses of 100-hertz frequency to cover the heart rate range from 348 bpm down to 148 bpm. If the actual heart rate is below 148 bpm, subsequent frequencies are gated until a heart rate as low as 40 bpm is computed.

Calibration Circuitry

A 10-hertz oscillator provides a 500-microvolt, peak-to-peak, square-wave signal for calibration of the three signal conditioners. Depressing the "calibrate" switch on the ESS provides plus 28 volts to an isolation switch, which in turn activates the 10-hertz oscillator. The switches from the Frank resistor network into the signal conditioners are opened and the switches from the oscillator to the signal conditioners are closed, allowing the calibrate signal to enter each signal conditioner. The switch at the input to the heart rate is opened so that the heart rate system is effectively disabled during calibration.

Electrode Impedance Check

The 10-hertz oscillator also provides a 0.5-microampere constant current for a checkout of electrode-to-skin impedance. The "electrode select" switch is rotated to the desired electrode position, activating the oscillator and allowing the checkout current to flow to the subject's body through the selected electrode. The readout circuit and meter are connected to the preamplifier output of the same electrode. The 0.5-microampere current flows through the electrode into the body and through the RS electrode to ground. The current flowing through the impedance causes a voltage that is proportional to the impedance to appear at the preamplifier of the electrode being measured. This voltage goes to the readout circuit, which amplifies and rectifies the square wave and drives a meter. The meter readout, located on the module front panel, is scaled down from 100 kilohms to 0 ohm for the impedance check.

Subject Isolation Check

When the "electrode select" switch is in the isolation position, the ground return is disconnected from electrode RS, and the 10-hertz oscillator output is connected to RS. The preamplifier output from electrode N is connected to the filter and readout circuit and drives the VCG panel meter. The 0.5-microampere current injected through the RS ESP, RS electrode, and the body can flow to ground only through a stray leakage path. The voltage developed on the body is proportional to the impedance between the body and the ground (because the current is constant and its amplitude is known). This voltage is sensed by the N electrode preamplifier and goes to the filter. The primary function of the filter (a single-pole, active, low-pass filter with a rolloff at 10 hertz) is to filter 60-hertz noise that may be picked up by the subject's body. The signal then goes to the readout circuit, which amplifies and rectifies the square-wave signal and drives the meter. For an isolation check, the meter readout is scaled up from 370 kilohms to 2.2 megohms. Midscale corresponds to 1 megohm, the minimum acceptable reading for the measurement.

IN-FLIGHT OPERATIONS

The VCG system supported three Skylab medical experiments: the lower-body negative-pressure experiment (M092), the metabolic activity experiment (M171), and the vectorcardiogram experiment (M093) (refs. 4 to 6). The arrangement of the various apparatus used to perform these experiments in the Skylab orbital workshop is shown in figure 11. Experiment M092 used the lower-body negative-pressure device (LBNPD) to simulate the effect of gravity upon each crewman. The subject's lower body (from the waist down) was subjected to pressure lower than cabin ambient to achieve this effect (fig. 12). The subject's condition was constantly monitored with the VCG and an automatic blood pressure measuring system (BPMS) during the test. The purpose of experiment M092 was to obtain information concerning the time course of cardiovascular changes in weightlessness and to provide data to predict the orthostatic intolerance and impairment of physical capacity that were expected when the crewmen returned to Earth. A bicycle

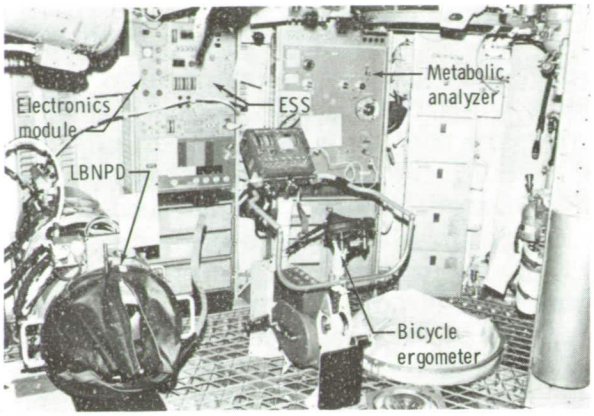


Figure 11.- Experiment equipment in Skylab orbital workshop.

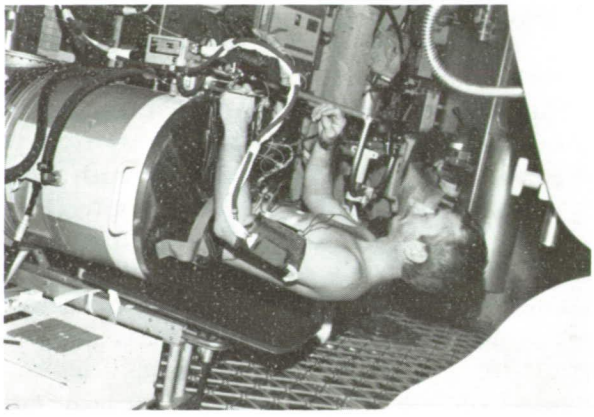


Figure 12.- Subject in M092 LBNPD.

ergometer, the BPMS, the VCG, and a metabolic analyzer were used in experiment M171 to determine if weightlessness progressively altered crewmen's work capability.

The primary use of the VCG, however, was for experiment M093, in which vectorcardiograms were taken continuously during a 17-minute experiment protocol that provided periods of rest before and after a short period of exercise on the ergometer. The purpose of the M093 experiment was to detect those changes in the electrical activity of the crewmen's hearts that are associated with prolonged space flight and to correlate these vectorcardiogram changes with those known to occur after special physiological intervention. For better appreciation of the experiment and as an aid to understanding the various VCG hardware functions, an M093 experiment protocol is presented. Two crewmen (subject and observer) were required to perform an experiment. The procedure was as follows.

1. The observer helps the subject apply electrodes to eight marked sites on the upper part of the subject's torso.

2. The subject mounts the ergometer and connects the electrode harness to the SIB, which is attached to the ergometer control panel (fig. 13).

3. The observer uses the VCG electronics to measure the subject's electrical isolation from the structure ground, then verifies that the impedance of each electrode is below 100 kilohms.

4. The observer sets the gain of each VCG signal conditioner to the assigned value for the subject, then turns on the onboard recorders.

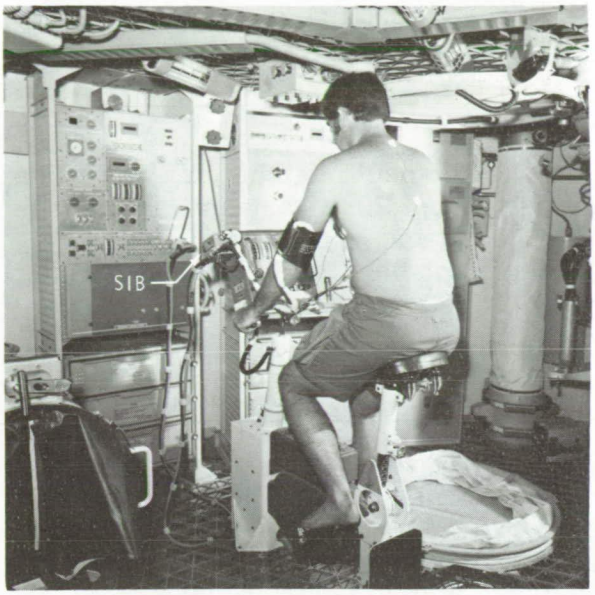


Figure 13.- The M093 experiment configuration.

5. The observer calibrates the signal conditioners by using the "calibrate" switch on the ESS.

6. The subject remains motionless for 5 minutes.

7. The subject pedals the ergometer for 2 minutes at 150 watts. The observer monitors the subject's heart rate, displayed on the heart rate meter.

8. The subject rests for 10 minutes

9. The observer performs a post-run calibration, verifies the electrode impedances, deactivates the recorders, and helps the subject remove the electrodes.

Results obtained from the in-flight experiments are given in references 4 to 6.

DATA SYSTEM

The four analog outputs from the VCG system (heart rate and X, Y, and Z axes) were scaled to be within a 0- to 5-volt range for input to telemetry. The heart rate was sampled 40 times each second; each VCG axis was sampled approximately 300 times each second. The 8-bit data format allowed resolution to 20 millivolts. The data were recorded on two onboard tape recorders, then transmitted to Earth when the Skylab was within range of a receiving station. After approximately 4 hours of various kinds of data including VCG had been recorded, the data were "dumped" to a selected receiving station at a rate 22 times the recorded speed. The dumped data supplemented real-time data so that VCG data from a complete protocol were obtained.

CONCLUDING REMARKS

The Skylab vectorcardiograph system performed its intended function without a failure. The principal investigators for the three experiments obtained the vectorcardiograph data they required. In fact, the large amount of data obtained from 170 days of in-orbit activity will be undergoing analysis for some time.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, February 15, 1975
948-60-90-93-72

APPENDIX

SKYLAB VECTORCARDIOGRAPH SPECIFICATIONS

The following paragraphs state the performance specifications for the Skylab vectorcardiograph. Applicable paragraph numbers from the American Heart Association "Recommendations for Standardization of Leads and of Specification for Instruments in Electrocardiography and Vectorcardiography" are provided parenthetically after each specification.

1. Frequency Response

The frequency response of the signal conditioner shall be flat within ±0.5 decibel from 0.14 to 90 hertz. The frequency response from 90 to 100 hertz and below 0.14 hertz shall not exceed that limit established for the frequency response from 0.14 to 90 hertz. The frequency response at 0.05 hertz and 100 hertz shall be down no more than 3 decibels from that at 0.14 hertz and 90 hertz, respectively. There shall be a rolloff of 18 decibels per octave above 100 hertz (C1, B3).

2. Calibration and Timing Circuitry

All three VCG channels shall be simultaneously calibrated by the calibration and timing circuitry. The calibration signal will be a 10-hertz (±2) square wave of 0.5 ± 0.01 millivolt peak to peak applied simultaneously to the input of all three conditioning channels. Switching will be such that electrode source signals are not applied to the signal conditioners during calibration (C2).

3. Phase Angle Matching

A phase angle exists between the sinusoidal input voltage measured at the input terminals of one VCG channel and the sinusoidal output voltage of the same channel. The magnitude of the difference in this angle between any two of the three channels shall be no greater than 3.0 degrees over the operable frequency range (0.14 to 90 hertz) of the system and at any combination of gain settings of the individual channels. This phase matching shall be ascertained by test with an EMR Model 1410 frequency response analyzer or equivalent (C2).

4. Time Identification

The spacecraft time recorded on the data tape recorder will be correlated with instrumentation and voice-communication data (C3).

5. Frank Vectorcardiogram Resistor Network

A Frank vectorcardiogram resistor network will be used to normalize the seven electrical signals taken on the body into the three orthogonal electrocardiogram signals required for vectorcardiogram analysis (C4).

6. System Performance, Linearity, and Distortion

An increasing input signal amplitude shall provide an increasing output signal. The harmonic distortion shall be less than 1.0 percent over the frequency range of the signal conditioner (C5, B1).

7. Gain

Six switch-selectable gains shall be provided to produce the following relationships with an accuracy of ±5 percent (C5, B2).

Switch position	Gain (peak-to-peak input), mV (a)
6	1.2
5	1.8
4	2.4
3	2.9
2	3.6
1	4.4

[a]Two-thirds full-scale output swing.

8. Common Mode Rejection Ratio

The common mode rejection ratio at any gain shall be 60 decibels (1000:1) or more over the operable frequency range of 0.14 to 90 hertz. The system common mode rejection ratio shall be measured by shorting all eight electrode inputs together and applying a common mode signal between the shorted inputs and signal common (±10-V dc return) (C5, B4).

9. Noise

Upon simulating a subject with completely shielded resistors of 25 000 ohms between each active input lead and the ground lead, the equivalent input noise at any gain shall be less than 10 microvolts root mean square (rms) (C5, B5).

10. Output

With no input signal applied, the output shall be biased at 1.7 ± 0.2 volts with respect to signal common. The output impedance shall be the lowest value practicable to minimize the phase angle differential between the three VCG channels when the equipment is interfaced with the telemetry-channel input impedance of 1 megohm in parallel with a capacitor of 0.94 microfarad ± 5 percent. The VCG system manufacturer shall test and document the phase angle differential between the three pairs of VCG channels with the worst-case variations of capacitors (+5 percent and -5 percent) across the respective outputs. The manufacturer shall also demonstrate that the system meets all specifications when operating into the 1-megohm load only, and all specifications with the exception of the phase angle variation when the 0.94-microfarad capacitance is placed in parallel with these resistors (C5, B7).

11. Recovery Time

Recovery time (time required for the output to return to a "no signal" condition) after transient inputs of 2 volts peak to peak of either positive or negative polarity and of 100-millisecond duration shall not exceed 24 seconds (C5, B8).

12. Signal Conditioner

The signal conditioner shall be a true differential design. The required input impedance shall not be less than 40 megohms differential from 0.05 to 100 hertz. The impedance between either input terminal and signal common shall not be less than 40 megohms (C5, B9).

13. Vectorcardiogram Electronics

Current limiting shall be provided to limit the short circuit current flowing into the SIB under any conditions to 0.5-dc rms ampere or less. In addition, the VCG system circuits shall be designed such that under any normal conditions no more than 0.5-dc rms microampere of current shall be allowed to flow through the subject-electrode junction (except during electrode checkout or the ground isolation test).

The system shall provide protection against electroshock by limiting current in any ground return path connected directly to the subject to less than 200 peak microamperes in the event that the subject should contact a dangerous potential. The system shall be designed to provide this protection for voltages up to 141 V ac rms or 200 volts peak over the frequency range of direct current to 1 kilohertz. This protection shall be demonstrated by connecting the electrode input circuit to 115 volts ac 60 hertz, with respect to system ground, through a 500-ohm resistor. Current through each electrode lead shall be less than 200 peak microamperes when monitored during the test, and the system shall operate within specification limits at the conclusion of the test. This test shall be accomplished for each electrode lead that contacts the subject (C5, B11, A12).

14. Frank Vectorcardiogram Resistor Network

A Frank resistor network will be provided and configured as in figure 9. The value of each resistor shall be determined by the system design and chosen to optimize the transfer function accuracy. The resistors shall have a tolerance less than or equal to 1 percent (C5, B10, A4).

15. Input Range

The instrument shall meet specifications with input signals corresponding to those expected from the Skylab crewmen (C5, B11, A2).

16. Gain Stability

The gain stability at any specific setting shall be ±2.5 percent under the environments of orbital operation (C5, B11, A6).

17. Electrostatic Protection

The VCG system shall be able to withstand without degradation of performance characteristics the discharge between any electrode input and signal common of a 200-picofarad capacitor charged to 300 volts (C5, B11, A7).

18. Radiofrequency Interference

A 1-volt, peak-to-peak, 100 ± 5 kilohertz signal applied to the VCG system input shall cause no degradation to the VCG system performance as specified in paragraphs 1, 6 to 11, 16, and 19 (C5, B11, A11).

19. Power

The signal conditioner shall operate from a plus-10 and minus-10 (±1.0 percent) V dc power supply.

20. Stability

Step changes in supply voltage of up to ±1 percent about the nominal plus-10-volt and minus-10-volt values shall effect no change in the output exceeding 10 microvolts peak-to-peak referred to the input (C5, B11, A20).

21. Environmental Requirements

1. The VCG system shall operate to specification after subjection to the following tests (C5, B11, A21).

Test	Parameter
Random vibration	11.5g rms 1 min/axis + 5.8g rms 2 min/axis
High temperature	313 K (40° C) (4 hours)
Low temperature	233 K (-40° C) (4 hours)
Low pressure	1333 N/m^2 (10 mmHg)
Humidity	85- to 100-percent relative humidity (5 days)

2. The VCG system shall operate to specification during the following tests.

Test	Parameter
Low temperature	288 K (15° C)
High temperature	318 K (45° C)
Low pressure	13 332 N/m^2 (100 mmHg)

22. Differential Input

Each signal conditioner shall operate in accordance with the specifications of paragraphs 1, 6 to 11, 16, and 19 with a 0- to 0.5-V dc differential input superimposed between the inputs.

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