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MPL EXPERIMENTAL RUM

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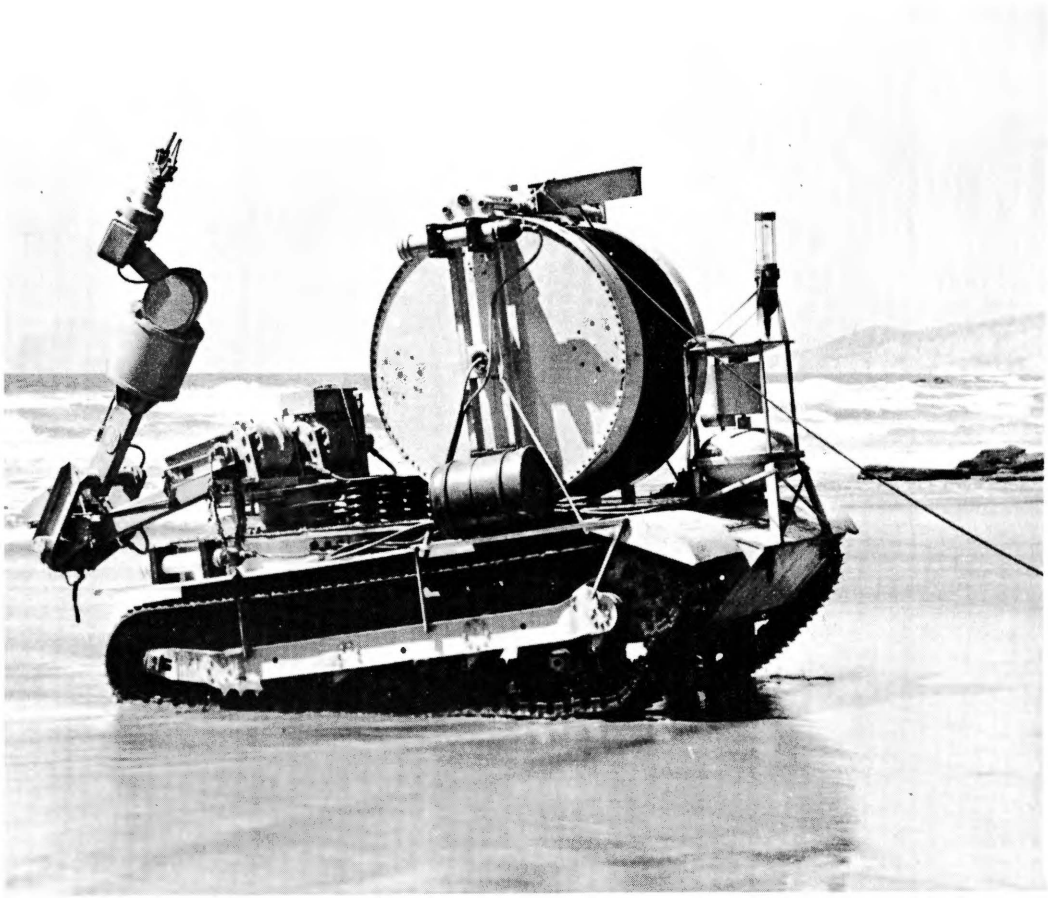

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Abstract

An experimental Remote Underwater Manipulator constructed at the Marine Physical Laboratory is described. Features of the design which permit operation at deep submergence in the ocean over 5 miles of small coaxial cable are discussed. Pertinent electronic circuits are shown and their general operation outlined.

Introduction

In November of 1958 the Marine Physical Laboratory undertook the construction of an experimental Remote Underwater Manipulator (RUM) as a part of a task, (7), under Contract Nonr 2216 with the Office of Naval Research. It was felt that by the adoption of a suitable design philosophy such a device, capable of operating at great depths, could be built utilizing, to a large extent, standard commercial components. Operating from a fixed installation over a length of several miles of control cable, the RUM would permit a significant increase in underwater installation work capability and a reduction of the required complexity of bottom-mounted oceanographic instrumentation.

The first tests of the MPL RUM were carried out in the San Diego Bay in May of 1959. The first ocean test was made on 5 May 1960.

This initial report covers the RUM design and construction in a manner which will outline the problems arising during its construction and describe their solution as well as present the philosophy followed in the design.

RUM Control Cable

The feasibility of constructing an experimental RUM was predicated on the availability of an electrical cable which could serve both to supply propulsion power and to provide a control channel capacity sufficient for all functions required for the remote operation. It appeared that a 5-mile length of a coaxial cable, similar to RG8/U, would transmit approximately 30 kw of 60 cps power at 4800 v rms and at the same time provide a useable pass-band of the order of 1 Mc for the control and telemetering functions. A 5-mile length of a special cable embodying the essential electrical characteristics of RG8/U but incorporating a heavy polyethylene jacket for greater abrasion resistance and a cadmium bronze center conductor for higher tensile strength has been procured from the Columbia-Geneva Steel Division of the U.S. Steel Corporation for use with the experimental RUM.

The results of attenuation tests run on this cable are given in Table I along with the complete specifications for the cable.

Maximum power transmission of this cable is limited by its loop resistance and voltage breakdown, but an average limitation for this cable occurs as a result of temperature rise of the insulation. The most severe condition in this regard occurs when the cable reel is nearly full. (Tests have shown a 20°C temperature rise after 5 hours of operation at a constant 1.5 kw power loss in the cable.) For an allowable temperature rise of 50°C the limiting average power in this case is expected to be of the order of 30 kw. The effective averaging time for such an average is 3 to 5 hours.

Power Distribution

The filter network which is used to separate the 60-cycle power from the signal spectrum in the cable is shown in Figure 1. The filter consists of a high-current low-pass network on each end of the cable which serves to isolate the cable from the power

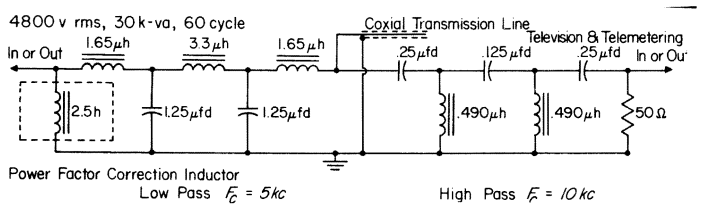


Figure 1. Signal-power separation filter.

Table I. RUM Control Cable

Manufacturer
Columbia-Geneva Steel Division, U.S. Steel Corporation

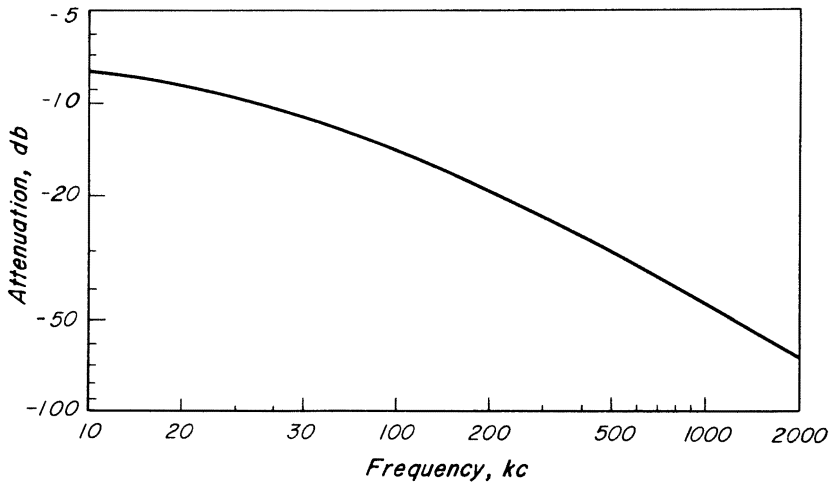
Manufacturers Type
Special American Coaxial, 7 Wire, 0.035" diameter each

Construction
7 wires, 0.035" diameter each
4% silver-plated grade 85 cadmium bronze
#32 silver-plated copper braid
Black polyethylene jacket to 0.500" diameter
Breaking strength — 630 pounds
Length — 26,400 feet

Electrical Resistivity

Braid	52.3 ohms at 20°C
Conductor	34.8 ohms at 20°C
Loop	87.1 ohms at 20°C

Characteristic Impedance
53 ohms



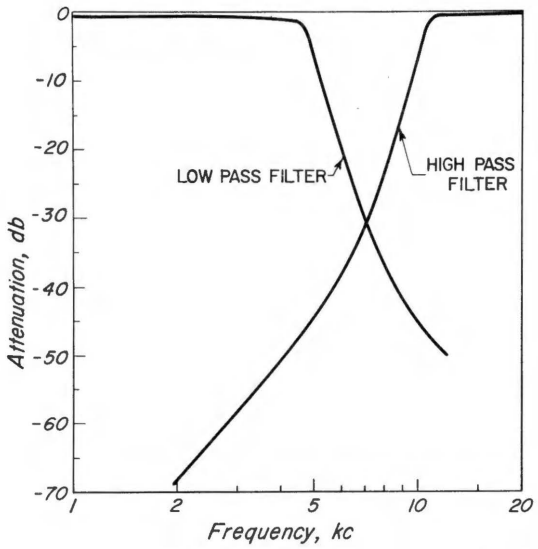


Figure 2. Signal-power separation filter frequency response.

line and propulsion circuits over the control and telemetering spectrum, and a high-pass network which rejects the 60-cycle power from the telemetering and control circuits. Two of these filters are used, one at each end of the cable. The cutoff frequency of the high-pass network is set at 5 kc while that of the high-pass signal filter is set at 10 kc. Cutoff characteristics of these filters are shown in Figure 2. The extremely high capacities required for the low-pass filter section necessitates the use of inductive power factor correction at each end of the cable to eliminate the losses which would arise from high reactive currents. The reactor and filter are packaged separately and mounted beside the high voltage transformer on the control van in Figure 3. The filter at the vehicle end of the cable is incorporated in the electronic compartment without additional cases so as to provide for the most compact mounting. The reactor is mounted externally in a sealed, oil-filled drum to provide cooling.

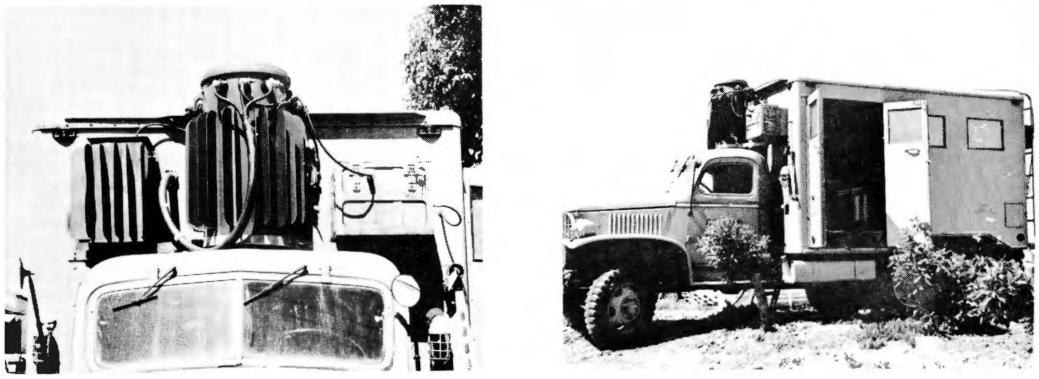


Figure 3. Control van housing remote control console and high voltage power circuits.

The 60-cycle power is carried on the line at a potential of 4800 v rms. At peak power of 30 kv-a there is an expected loss of 3 kv-a. In view of this and the normal 10 percent voltage regulation expected on the power line, all circuits in the RUM are designed to operate over a 20 percent variation of voltage. Input power from the power line is received at 230 volts or 117 volts and transformed to 4800 volts in the line transformer shown in Figure 3-A. A similar but uncased transformer is directly submerged in the transformer oil of the electronics compartment to provide 230 volt centertap-grounded power for distribution within the vehicle.

Signal Distribution

The frequency spectrum of the signals carried on the coaxial cable is shown in Figure 4. The control of the vehicle is accomplished by use of a number of telemetering carriers. Each carrier is amplitude modulated by 16 subcarriers which may be independently turned on or off to provide control functions. The subcarriers range from a 425-cps center frequency up to 2975-cps center frequency. A set of standard telegraph tone filters which have uniform bandwidth and are tuned to center frequencies uniformly spaced at a 170-cps center-to-center spacing, are used for separation of the subcarriers in the electronics of the vehicle. Carriers of 22 kc, 52.5 kc, and 70 kc center frequencies are used for these control functions giving a total capacity of 48 on-off control channels.

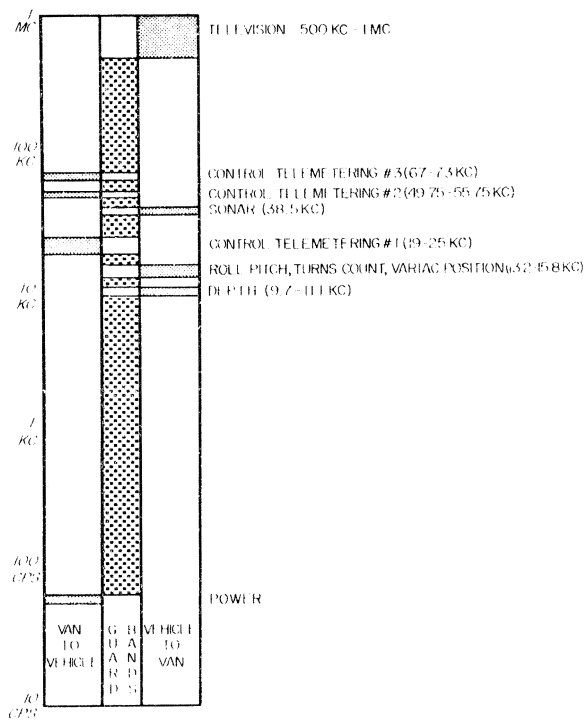


Figure 4. Frequency allocation of the signals carried on the coaxial cable.

Operational information is transmitted from the vehicle to the control van over another set of frequency bands. The band of 9.7 kc to 15.8 kc is used to transmit the pressure signal, pitch and roll, Variac shaft positions and two track turns count signals. Sonar information is transmitted at 40 kc with a bandwidth of 3 kc. Television signals occupy the remaining spectrum from 500 kc up to the cutoff of the cable at about 1 Mc.

The transmission characteristics of the over-all cable filter system are shown in Figure 5, along with the noise level at the output of the separation filter under full power operation.

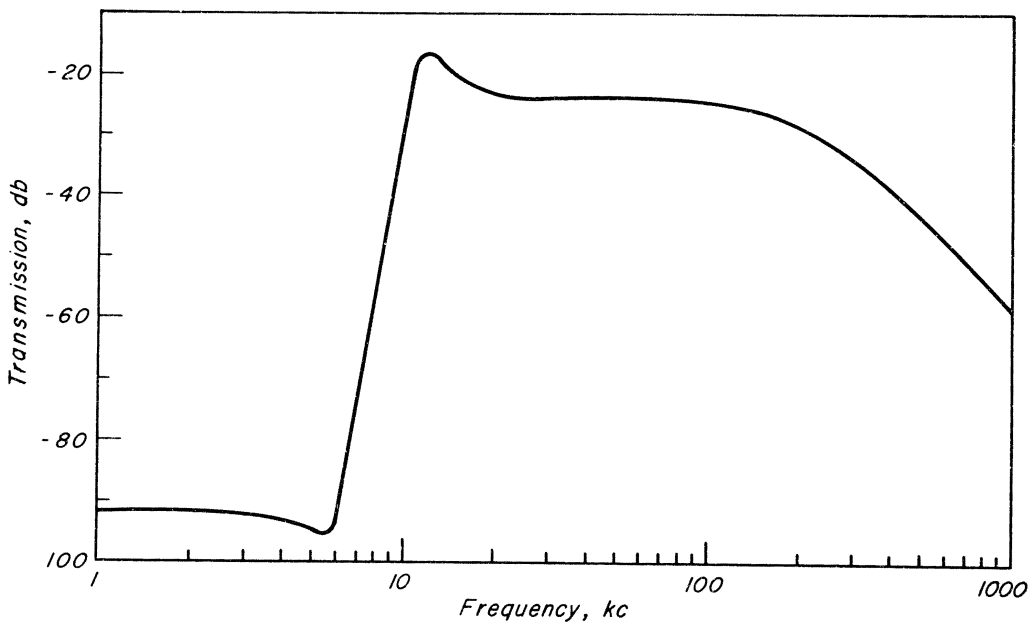


Figure 5. Transmission characteristics for the combined cable-filter system.

High-Pressure Design Considerations

A maximum ambient operating pressure of 10,000 psi was chosen as a design goal for the RUM. The high pressure influenced the design by pointing towards the direct operation of the majority of components in an ambient pressure equal to that of the surrounding water.

One of the most uncertain components with regard to operation completely submerged in a fluid was the dc electric motor. Initial tests were carried out on a fractional horsepower dc motor operating in a test bath of oil. A number of different oils were tested for a set of operating speeds, brush material and brush pressures. As a result of these tests it was determined that a reasonable life, in excess of 400 hours, could be expected if a slow-speed motor were used with a three-fold increase in brush pressure and operated in Richfield Spindle-X. Spindle-X is a high-speed spindle oil with an E.P. additive suitable for use in high torque gear trains. The presence of an E.P. additive seems to have a beneficial effect in the commutation, probably as a result of the reduced dielectric strength of the oil which accordingly reduces the violence of the arcing at the brush. As a result of these tests it was decided that dc motors could operate completely submerged in this oil, so that it would not be necessary to provide pressure cases and high pressure shaft seals.

Another component which was to be exposed to the high ambient pressure was a silicon power rectifier diode which would be used to convert the 60-ac power to dc for the propulsion motors. Several brands of power rectifiers were tested in a small pressure tank and found to fail at about 1000 psi. One special rectifier was designed and supplied to us which withstood a full 10,000 psi. A number of these were obtained for the rectifier banks, but unfortunately failed due to insufficient inverse peak voltage rating. The search for high-pressure rectifier components was not extended since it was felt this was a straightforward mechanical design problem and could, if necessary, be circumvented by the use of simple pressure cases and standard rectifiers.

Conventional electrical circuit breakers were employed for switching the main power and for the motor-reversing functions. These circuit breakers operate completely submerged in the Spindle-X oil of the propulsion compartment.

Micro-switches were originally installed in the indicator and limit-switch circuits, but proved to be unreliable in their operation when filled with the moderately heavy oil to be found in the power compartments. In their place simple spring contacts have been used for the track turns indicator circuits and an inexpensive normally closed push-button has been

used with excellent success for limit-switch applications on the motor-driven controllers.

Electronic circuits which would not withstand the high ambient pressure have been packaged in cylindrical pressure cases of the type shown in Figure 6. These pressure cases have been pressure tested to 20,000 psi. Special tapered nylon seals were developed which also have been tested at 20,000 psi. These are seen installed on the ends of the pressure case in Figure 6 and are shown in detail in Figure 7.

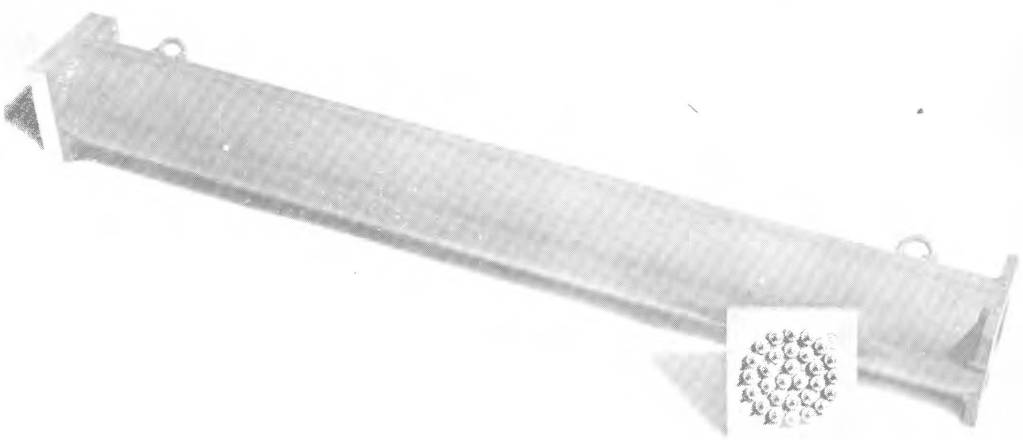


Figure 6. Pressure cases for electronics equipment (20,000 psi test).

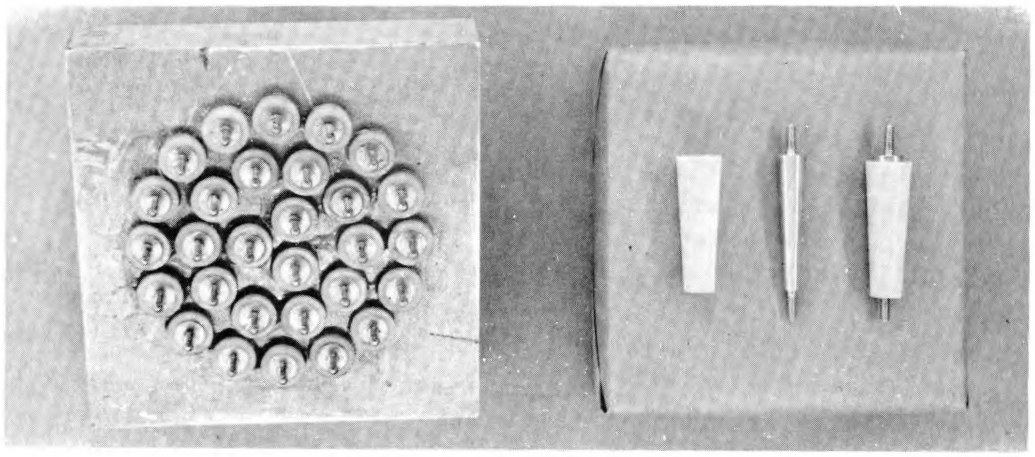


Figure 7. Tapered nylon electrical seals for use at 20,000 psi.

Large capacity neoprene bellows have been provided to compensate for volume changes in the oil due to temperature and pressure variations. These bellows are spring-loaded to provide a differential overpressure of a few psi in the oil of the interior of the hull so as to prevent salt water contamination of the oil. The individual wheel bearings of the track idler wheels were similarly pressurized by means of small bellows to permit their operation in high ambient pressure without the danger of salt water corrosion of the bearing surface.

Cable Reel

A storage capacity for 5 miles of cable is provided by the cable reel of Figure 8. This reel utilizes the same oil-filled pressure release construction which is used throughout the vehicle. A dc torque motor is incorporated in one of the wide flanges to maintain a constant tension of 50 to 100 pounds on the cable. A levelwind and cable fairlead provides for unattended spooling and unspooling of the cable as the vehicle traverses the bottom. The other flange of the cable reel contains a high-voltage, low-noise slip ring to furnish continuous electrical connection to the coaxial cable.

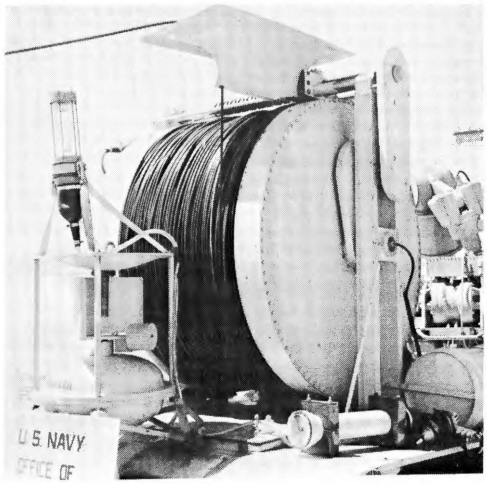


Figure 8. Cable reel with a capacity for 5 miles of cable, mounted on the RUM.

Hull Construction

The MPL RUM has been built on the basic hull and track assembly of an M-50 self-propelled rifle or "Ontos," provided for this purpose. The Ontos was stripped and reworked to provide four compartments as shown in Figure 9.

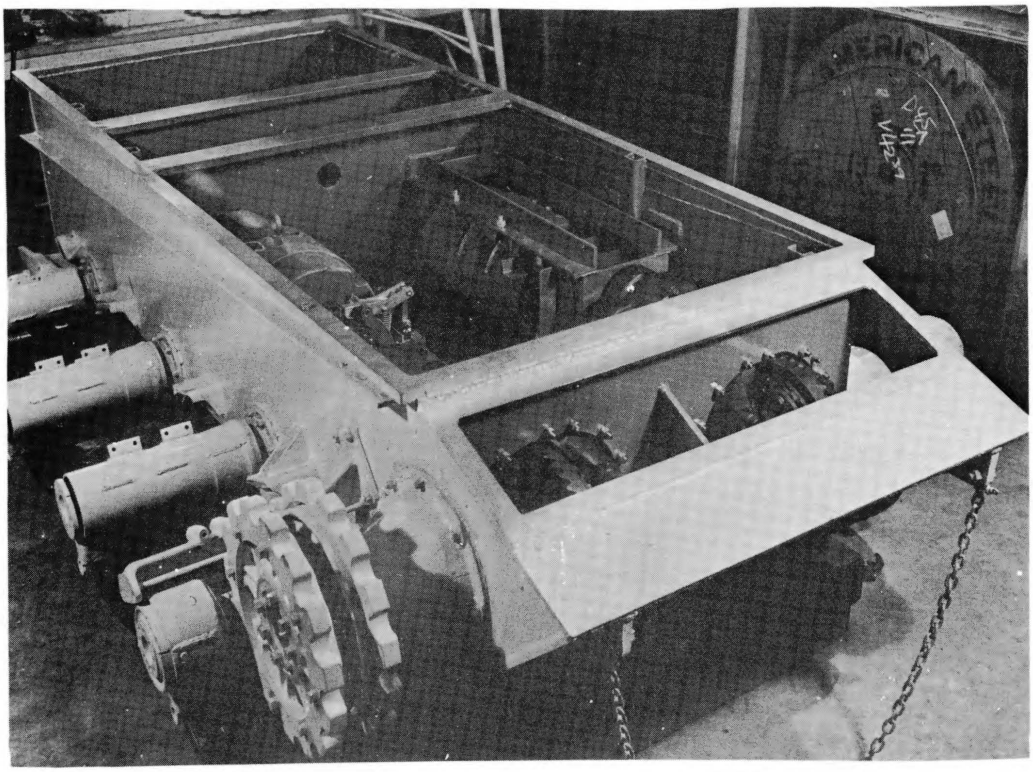


Figure 9. "Ontos" hull and track suspension, compartmented for installation of RUM components.

The main propulsion equipment occupies the major space. In this compartment are located the two independent drive motors, transmissions, power transformer, circuit breakers, Variac controllers, power rectifier, banks, and circulatory oil-filter system. Forward of the main propulsion compartment is the sprocket drive compartment which is filled with a heavy transmission grease and contains the rear-end truck axle drives used as the final reduction in the gear train. Just aft of the main propulsion compartment is the electronics compartment which accommodates the line filter and the electronic pressure cases for control telemetering circuits, sonar and TV control circuits and some of the signal relay switching circuits. The last compartment at the rear of the vehicle provides a mounting base for the manipulator and houses the dc power supplies required for its control.

Main Propulsion

Propulsion of the RUM is accomplished through independently driven motors to the two tracks. Two General Electric dc motors, 7-1/2 hp, 800 rpm, are used to provide power. Each of the two motors is direct-coupled through the fixed gear reduction of 7:1 of a 2-1/2 ton Chevrolet truck transmission to a 2-1/2 ton truck rear end which was modified by replacing the planetary gears with a solid spider welded to the bevel gear. The drive axle is splined to this gear, and couples to the track sprocket with the chain coupling originally provided on the "Ontos." The two differential housings are mounted in a bulkhead which separates the forward transmission housing (filled with SAE-140 transmission lubricant) from the motor compartment (filled with Spindle-X). Both the motor and transmission compartment are coupled to the ambient sea pressure through compensating bellows. The arrangement may be seen in Figure 10.

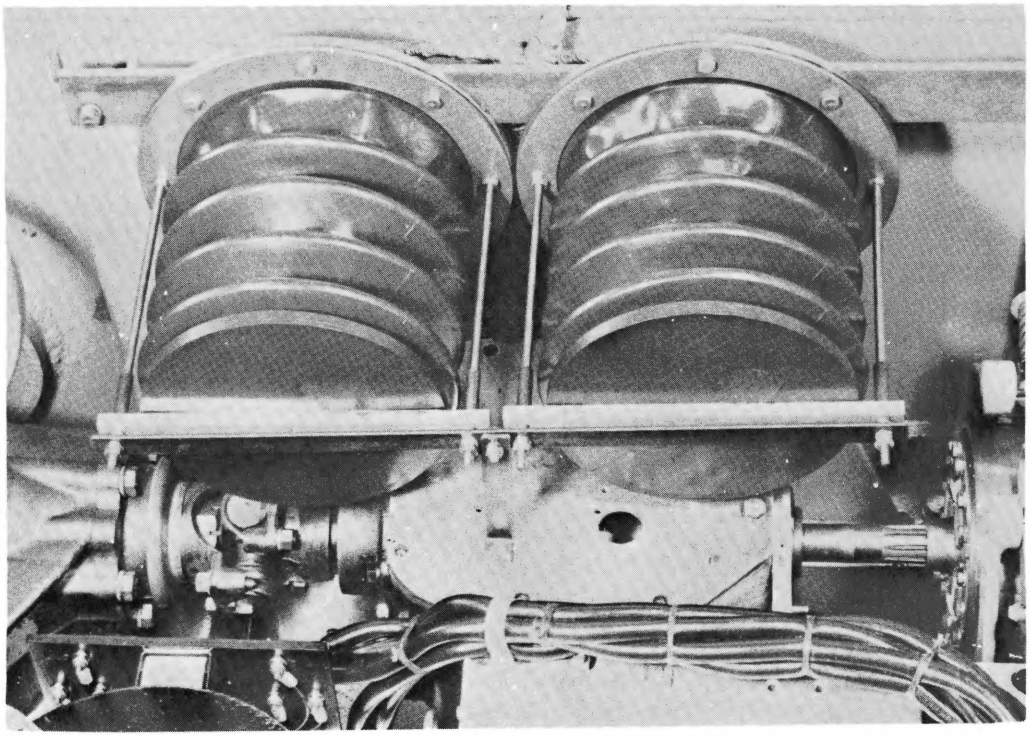


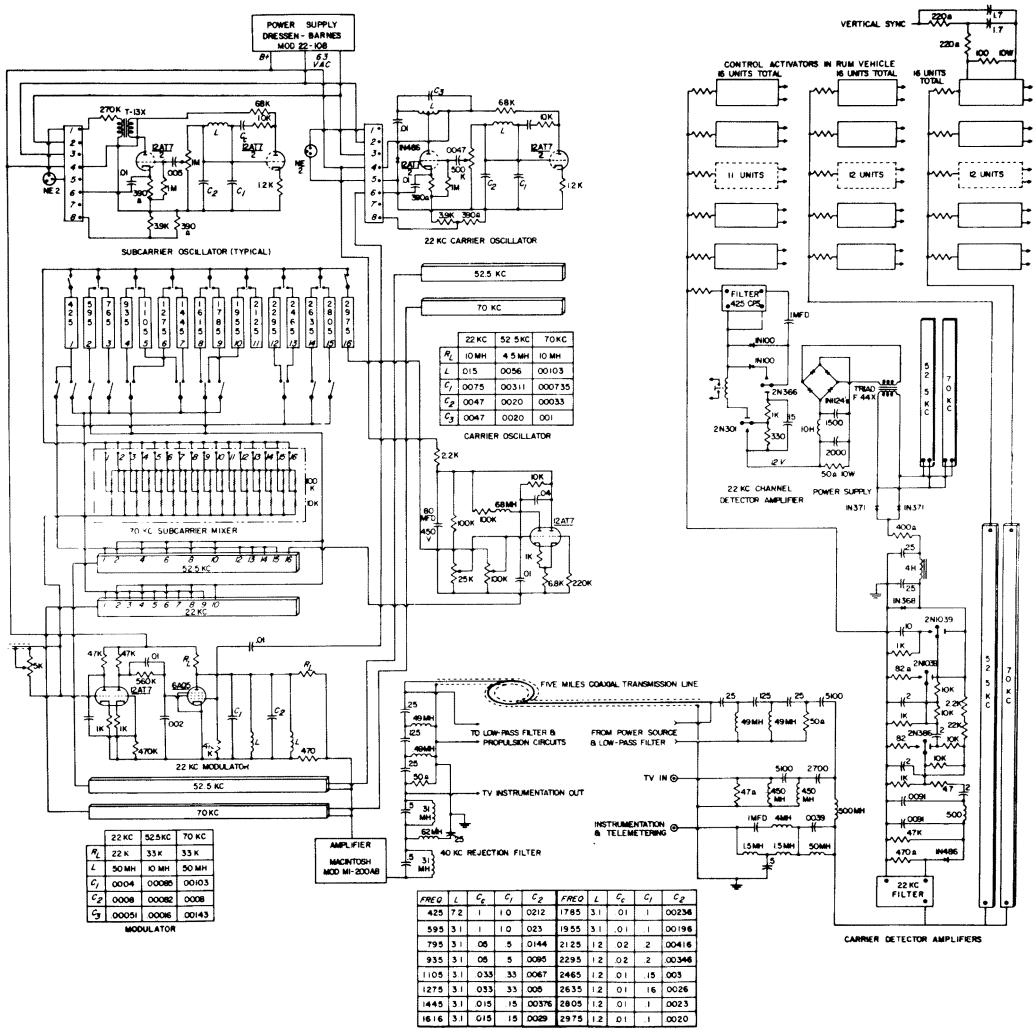
Figure 10. Pressure compensating bellows installed in the main propulsion compartment.

Independent two-track control is provided by 5 on-off control channels. Two channels for forward-reverse control of each track serve to position a Variac through a motor-cam linkage and associated cam-controlled field reversing circuit breakers so as to provide continuous control of drive power from full-on through zero to full-off. Limit switches on the Variac motor drive system provide safety stops to prevent mechanical damage on the control system. On each motor shaft is mounted a cam-controlled electric brake which operates both in the zero power control region and also when the main power is disconnected. The output of each Variac drives the motors through a full-wave silicon rectifier bridge to provide the required dc power.

Control Circuitry

In an attempt to provide the maximum reliability all control functions for operation of the RUM are carried on through the use of on-off control channels. Switches in the control console select the appropriate subcarriers which are mixed and fed to a carrier modulator tube. The modulated carrier is transmitted to a MacIntosh power amplifier and thence to the matching network for the coaxial cable. The circuitry for this telemetering control generator is shown in the upper part of Figure 11. Individual oscillators of a modular plug-in construction are housed in a single chassis, shown in Figure 12, and provide all of the subcarrier frequencies as well as the three carrier frequencies. Table II lists the channel assignment for the required control functions. The telemetering signals are sent down at a level of 10 watts so as to reduce the required amplification at the vehicle end of the cable and to provide a safe signal-to-noise ratio margin at the end of the 5 miles of cable.

The control circuitry in the vehicle is completely transistorized and consists of a channel selector filter followed by a suitable amplifier and detector circuit whose output drives a bank of subcarrier filters for control channel separation. The schematic for the vehicle control telemetering is shown in the lower part of Figure 11. The output of the subcarrier filters feeds a transistorized detector-amplifier which drives a controlling relay capable of handling any of the 110-volt control circuits of the vehicle.



	22 KC	52.5 KC	70 KC
R_L	10 MH	4.5 MH	10 MH
L	015	0056	00103
C_1	0075	00311	000735
C_2	0047	0020	00033
C_3	0047	0020	001

	22 KC	52.5 KC	70 KC
R_L	22 K	33 K	33 K
L	50 MH	10 MH	50 MH
C_1	0004	00085	00103
C_2	0008	00082	0008
C_3	00051	00016	00143

FREQ	L	C_c	C_1	C_2	FREQ	L	C_c	C_1	C_2
425	72	1	10	0212	1765	31	01	1	00234
595	31	1	10	023	1955	31	.01	1	00196
795	31	08	5	0144	2125	12	02	2	00416
935	31	08	5	0095	2295	12	02	2	00348
1105	31	033	33	0067	2465	12	01	15	003
1275	31	033	33	005	2635	12	01	16	0026
1445	31	015	15	00376	2805	12	01	1	0023
1616	31	015	15	0029	2975	12	01	1	0020

Figure 11. Control telemetering schematic.

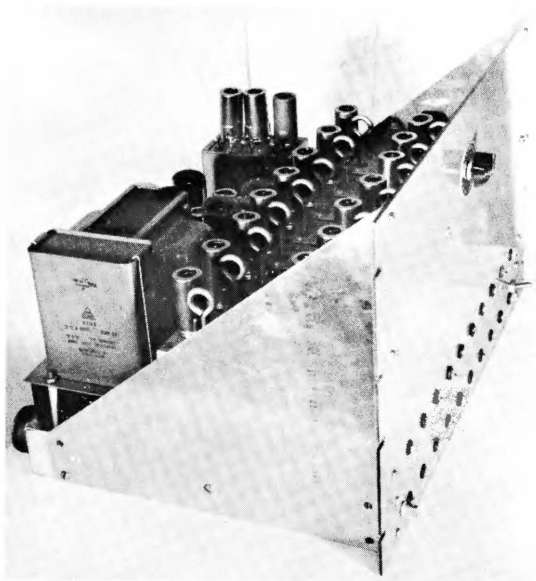


Figure 12. Telemetering oscillator chassis.

Table II. Control Function Channel Assignments

Frequency	22 kc	52.5 kc	70 kc
425	Propulsion spare on	Manipulator speed	Manipulator on
595	Propulsion on spare	Propulsion on	Grip open
765	Camera pair select		Grip closed
935	Port track fwd spare	Port track fwd	Azimuth cw
1105	Elevation joint down		Azimuth ccw
1275	Port track rev spare	Port track rev	Flex up
1445	Elevation joint up		Flex down
1615	St'bd track fwd spare	St'bd track fwd	Shoulder cw
1785	Sonar disable		Shoulder ccw
1955	St'bd track rev spare	St'bd track rev	Upper arm up
2125			Upper arm down
2295		Iris open/focus near	Forearm up
2465		Iris closed/focus far	Forearm down
2635		Sweep rate slow	Wrist cw
2805		Step switch	Wrist ccw
2975		Vertical sync	Iris focus select

Sonar

A simple searchlight sonar was constructed for the experimental RUM. This sonar operates at a frequency of 40 kc with a pulse length of 0.2 ms and incorporates a fixed transducer with a rotating parabolic steel mirror for beam formation. Horizontal beam characteristics of the transducer-reflector combination are shown in Figure 13. The vertical beam is somewhat narrower than optimum for use with the RUM. However, the preliminary operation has shown that it does give a satisfactory representation of the bottom terrain, and thus serves as a basic guide for navigation. The useful range of the sonar is approximately 40 yards. A disabling circuit may be operated by one of the telemetering control channels so as to permit the use of the sonar in a passive mode. In this mode the vehicle heading may be obtained by observing a fixed sonar beacon, and sonic ranging can be accomplished by measuring the travel time from a pair of fixed beacons.

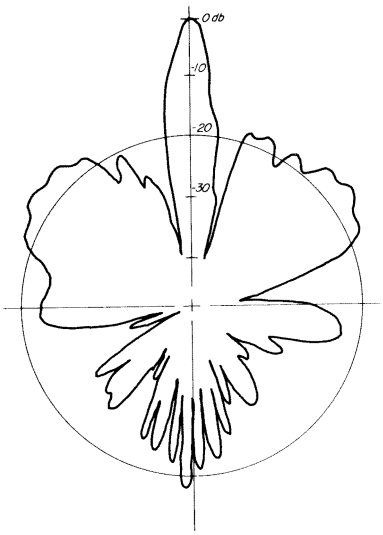


Figure 13. Horizontal beam characteristics of the sonar transducer-reflector combination.

A schematic diagram of the sonar is shown in Figure 14. Parallel circuitry has been used throughout for greater reliability, and a logarithmic output amplifier is incorporated to reduce the required gain stability and dynamic range of the transmission channel. The sonar signal is transmitted directly through the 40-kc channel on the coaxial cable. Presentation at the control console is on a PPI display. A typical reverberation display is shown in Figure 15. Figure 15-A illustrates the very high reverberation associated with the surf zone near the Scripps pier. The pier pilings are visible to the left of the display as two lines of targets running from top to bottom. Figure 15-B shows a similar sonar presentation where a higher contrast is observed on the pier piling echoes than is apparent in Figure 15-A.

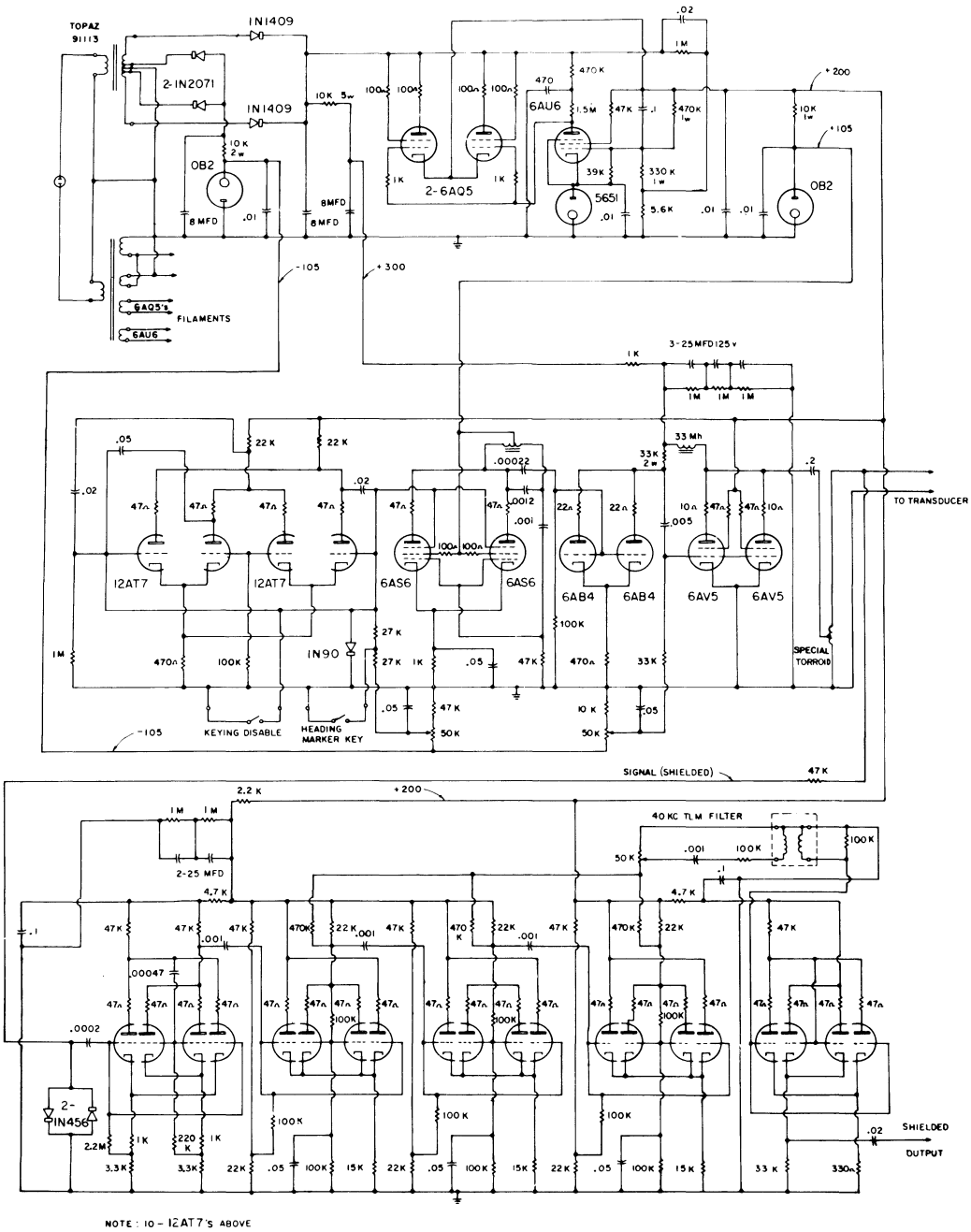


Figure 14. Sonar schematic diagram.

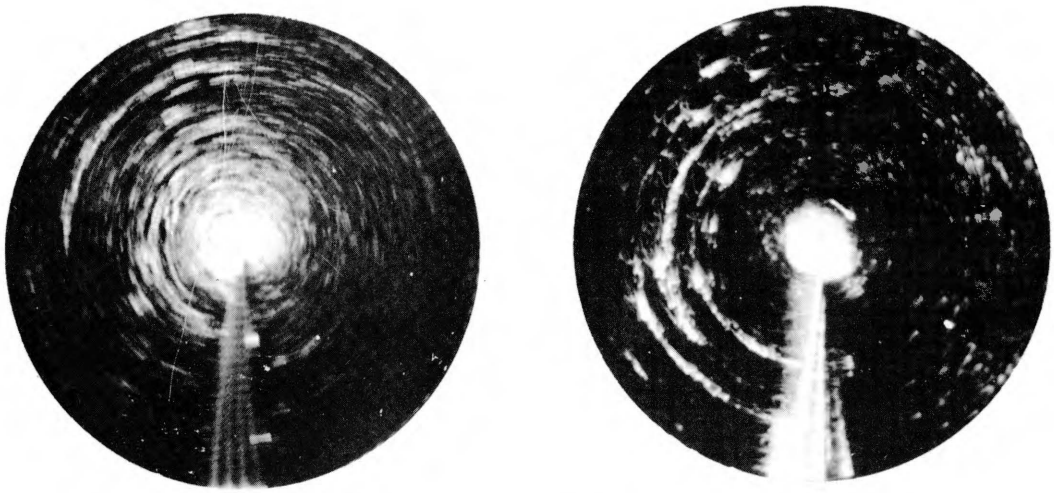


Figure 15. Typical sonar display of reverberation.

TV Equipment

A six-camera capacity TV system is used to provide visual coverage of various sectors as dictated by the operation requirements. The location of these cameras is optional, and it is expected that several arrangements will be used in the subsequent sea tests. For example, a typical arrangement would have four cameras mounted on the front, sides and rear of the RUM for general viewing of the terrain surrounding the vehicle, and two cameras mounted on the boom to provide a "steroscopic" view of the immediate manipulator area.

Two vertical scanning rates of 15 cps and 3 cps permit a selection of two resolutions for details or general viewing. The slow-scan rates permit the use of a 500-kc video bandwidth and increase the effective sensitivity of the vidicon.

The camera units are packaged in individual pressure cases as shown in Figure 16. These pressure cases are provided with conical lucite pressure windows. Each camera is provided with two remotely controlled motors for adjustment of iris and focus. The camera electronics are completely transistorized except for the vidicon.

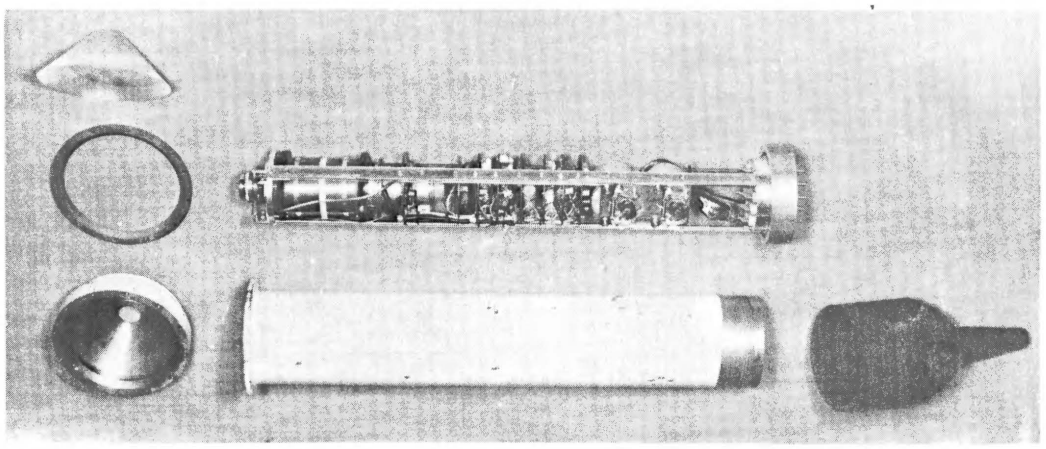


Figure 16. Television camera and case components.

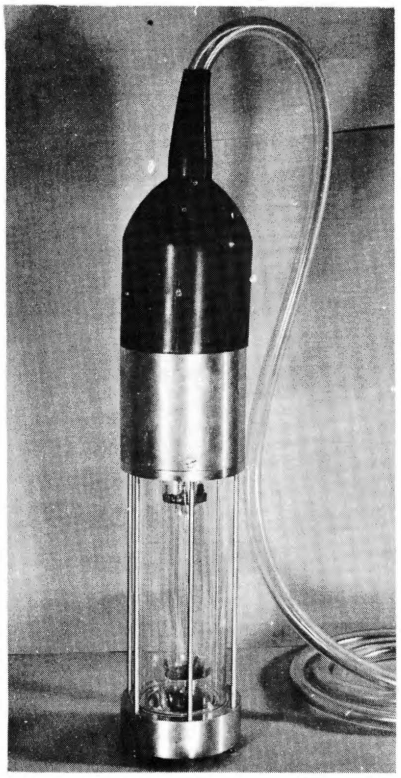


Figure 18. Mercury vapor light and pressure case.

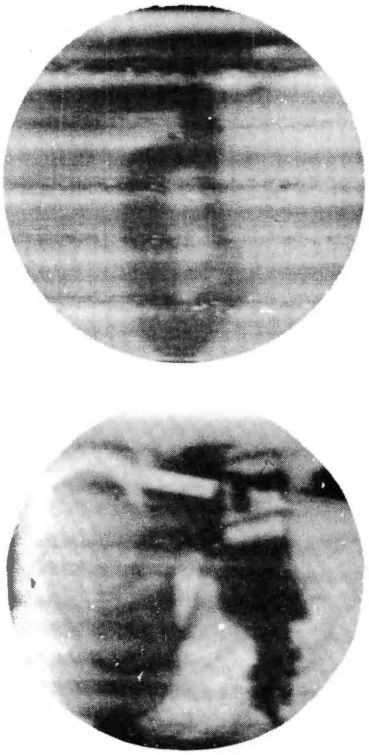


Figure 17. Typical TV presentations.

Control signals for the 6 cameras are supplied by the control unit which is housed in one of the standard electronic pressure cases in the electronics compartment. The control unit generates the required sweep and blanking signals and also contains a modulated RF amplifier to transmit the video information up the control cable on a 1-Mc carrier. An electronic switch is provided which allows two camera video signals to be transmitted on alternate frames to two separate monitoring CR tubes on the control panel. In this way, the single video channel can transmit the two independent pictures required for steroscopic viewing. A remotely controlled stepping switch is used to select the camera or camera-pair to be observed. Typical TV presentations are shown in Figure 17. A 100-watt mercury vapor lamp is housed in a pressure case as shown in Figure 18 to provide illumination for the TV cameras.

Vehicle Instrumentation

In addition to the sonar and TV equipment, other instrumentation is provided in the vehicle to transmit basic operational information back to the control console.

A Vibratron pressure gauge is used to provide a high-resolution measurement of vehicle depth over an FM-telemetering link which operates in the bank of 9.7 to 13.5 kc. The unit is capable of detecting depth changes of 4 feet over a pressure range of 0 — 2000 psi. Absolute accuracy is ±0.2 percent or ±8 feet.

Four potentiometer shaft positions are telemetered to the control van as variable voltages. Two of the 4 shaft positions provide pitch and roll information while the other two indicate the position of the motor driven Variacs. Superimposed on the carriers for the Variac position is an amplitude modulated track turns counter signal which may be used as a coarse odometer by the operator.

A schematic of the vehicle instrumentation package is shown in Figure 19.

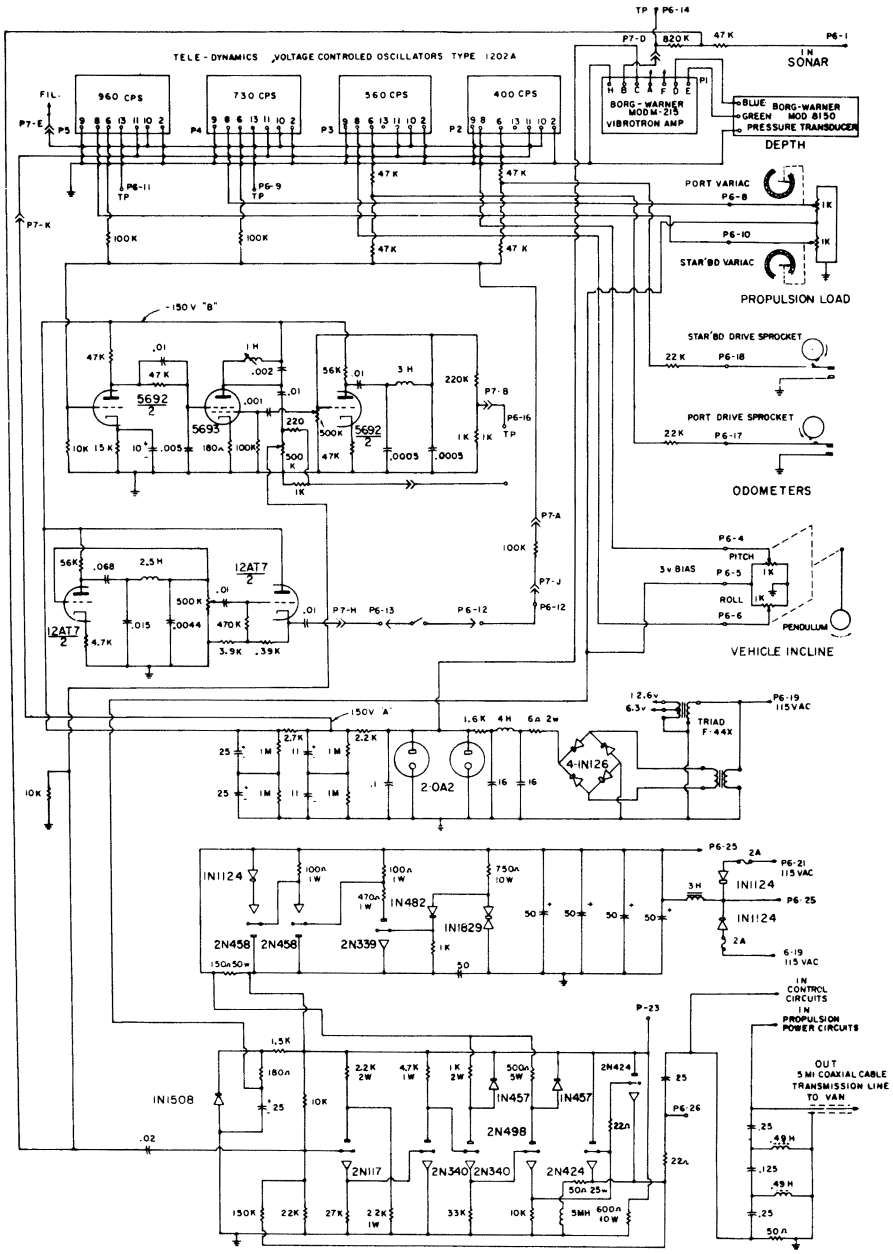


Figure 19. Vehicle instrumentation schematic.

Manipulator

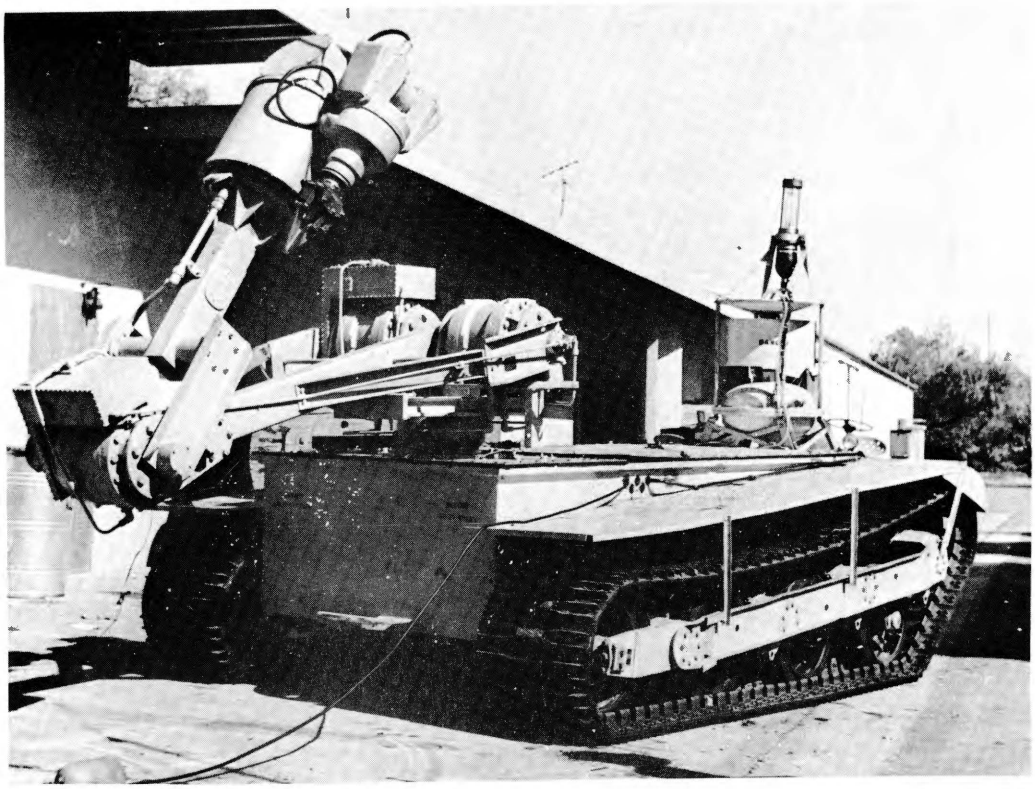


Figure 20. General Mills manipulator and boom mounted on RUM.

The manipulator for the MPL RUM was obtained from General Mills as a complete assembly ready for installation in the rear compartment. As may be seen in Figure 20 it consists of a model 500 manipulator arm mounted on the end of an articulating boom which has three degrees of freedom: base rotation, lower boom elevation and elbow elevation between lower and upper boom. The manipulator itself has the standard set of 5 motions: shoulder rotation, shoulder pivot, elbow pivot, wrist rotate and hand grip. These functions, combined with power on-off, fast-slow and forward-reverse control, require 18 of the off-on control channels. The manipulator capabilities are as follows:

Gross lifting capability with hook . . .	1500 lbs at 10 ft
Maximum outreach	15 ft
Manipulator lifting capability	500 lbs
Wrist torque	100 ft-lbs
Hand closing force	100 lbs

The manipulator arm itself is powered by dc motors while the boom operates from a hydraulic system position servo-coupled to dc control motors.

Operator's Console

The operator's control console is mounted in the van of Figure 3. The control panel layout is shown in Figure 21. The operator is provided

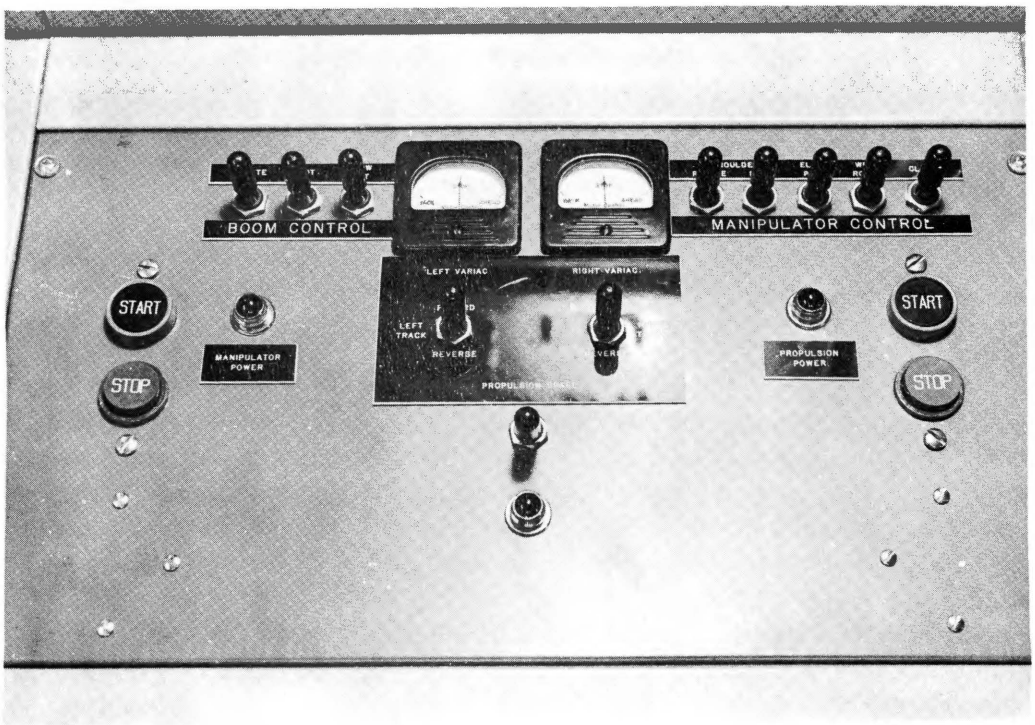


Figure 21. Control panel switch layout.

with a set of forward-reverse switches for the various control functions. In the center of the panel are the right and left control switches and the associated meters for Variac positions and roll and pitch. On the upper left of the panel are the 3 boom control switches, with the manipulator control switches mounted at the upper right-hand side. A main power disconnect for propulsion power and one for manipulation power are controlled by the push buttons on either side of the panel. Two meters present the telemetered Variac positions for each track to the operator. A foot switch is provided for fast-slow manipulator speed selection.

The complete console is shown in Figure 22. The lower left-hand tube is the PPI sonar display, the lower right-hand tube is a single tube TV display, and the upper pair of tubes provides the "steroscopic" camera display used for manipulation. The pressure gauge read-out appears on the digital display panel in the right-hand section of the rack immediately above the two mechanical track turns counters. The remainder of the panel space is occupied by the electronic circuits associated with the telemetering and display equipment and these are not of immediate concern to the operator during actual control of the vehicle.

Figure 22. General view of control console.