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TECHNICAL NOTE

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PROJECT ECHO—STANDBY RECEIVER SYSTEM

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SUMMARY

The Echo I satellite receiving system at the Bell Telephone Laboratories facilities at Holmdel, New Jersey, required a 2390-Mc standby receiver system to maintain operation during possible failures of the primary maser receiver. This paper describes the details of the two matched parametric amplifiers that were used to provide the standby receiver. The use of this system in the initial Moonbounce experiments and in Project Echo is described. The details of an emergency operation at the beginning of a balloon pass are also presented.

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PREFACE

The Project Echo communications experiment was a joint operation by the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), the Naval Research Laboratory (NRL), and the Bell Telephone Laboratories (BTL). The equipment described herein, although designed by BTL as part of its own research and development program, was operated in connection with Project Echo under contract NASW-110 for NASA. Overall technical management of Project Echo was the responsibility of NASA's Goddard Space Flight Center.

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INTRODUCTION

The Echo I 2390-Mc receiving system is shown in block diagram form in Figure 1. The masers and parametric amplifiers are shown in parallel in the overall system. Since the parametric amplifier system must provide performance similar to that portion of the primary system it parallels, it must have comparable gain and bandwidth and an acceptable noise figure.

In addition to the general requirement that the parametric amplifier system be independent of the maser system, there were a number of specific requirements. The input frequency was 2390 Mc and the output frequency was 70 Mc. For system compatibility the parametric amplifier system, including the down-converter and IF amplifier, had to provide at least 60 db overall gain. The minimum bandwidth for the planned experiments was 5 Mc. Considerations of the transmitter power and antenna gain at the Jet Propulsion Laboratory facility at Goldstone Lake, California, the path loss, and the Holmdel antenna gain and noise temperature, indicated that a noise temperature of 300°K would be acceptable for the standby system.

In addition to the electronic requirements, size and weight limitations were imposed. The parametric amplifiers (paramps) had to share a small antenna cab mounted on the horn antenna with the maser and the test equipment. The completed paramp system had to weigh less than 300 pounds and occupy a maximum space of 3 feet in width and length, and 4 feet 8 inches in height.

The completed paramp system provided a total gain of 63 db in each channel with 3-db bandwidths of 15.5 Mc and 21.5 Mc respectively. The overall system temperatures

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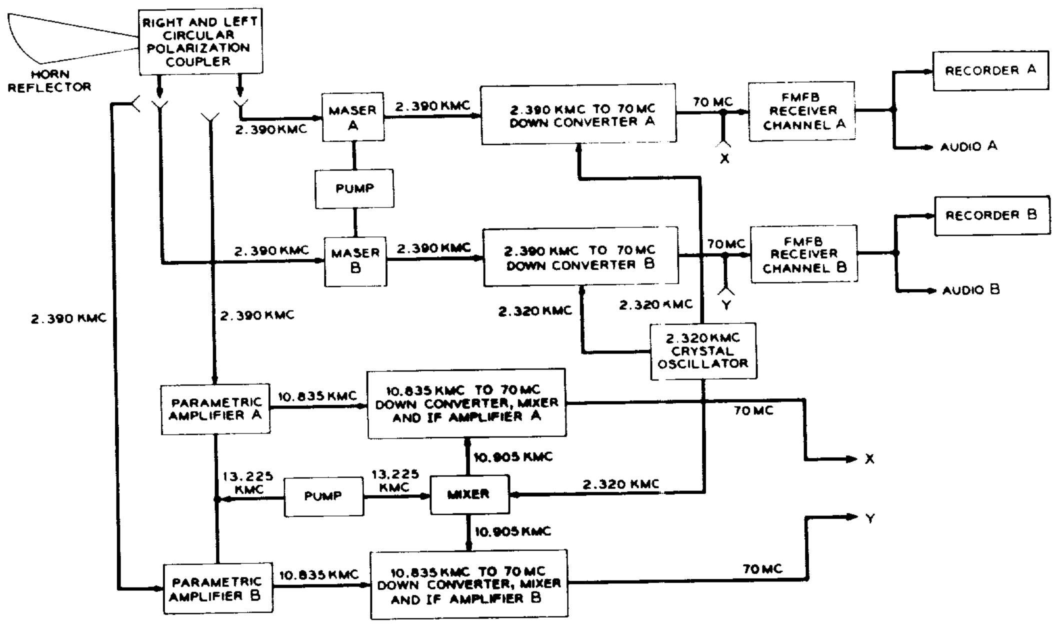

Figure 1—Overall receiving system for Project Echo

were 283°K and 297°K respectively. The system gain varied ±0.5 db over an hour* of operation associated with a balloon pass.

PARAMETRIC AMPLIFIER SYSTEM

The parametric amplifier system consists of two identical negative-resistance up-converters using a common pump source, resistive down-converters, and a frequency-stabilizing circuit. The various parts of the complete system are detailed in the block diagram of Figure 2.†

The choice of the negative-resistance up-converter mode of operation was dictated by gain-stability considerations and by the availability of low-insertion-loss isolators. Low-loss circulators were not available when this system was designed. It has been shown (Reference 2) that operation of a parametric amplifier with the idler frequency terminated in the varactor diode series resistance provides the lowest noise temperature. This mode of operation requires a reflection-type negative-resistance amplifier using a

*This hour includes the 12 to 20 minutes of the actual pass and the time for pre- and post-calibration of the system.

†The single parametric amplifier is similar in mode of operation to that described by Uenohara and Seidel (Reference 1).

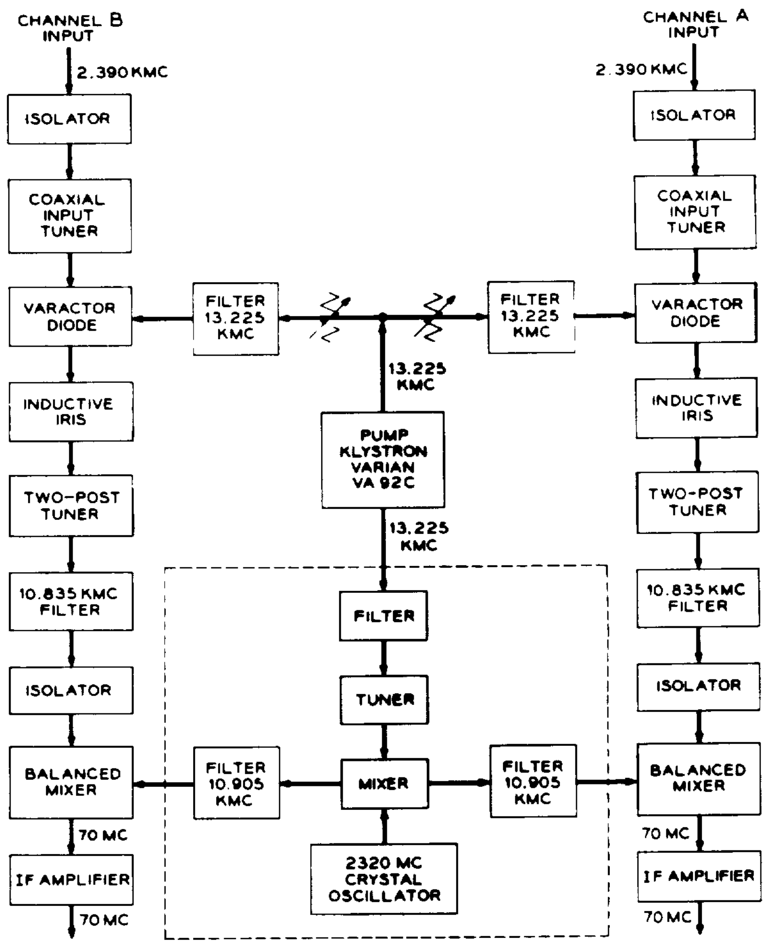

Figure 2—The parametric amplifier system

circulator. All the gain is achieved from the negative resistance. The negative-resistance up-converter achieves part of the gain from negative resistance and part from the frequency ratio of the up-conversion. Thus, for a given gain, the up-converter will generally have better gain stability than the reflection amplifier. The decrease in noise temperature associated with the reflection mode of operation was offset, in this case, by the increased insertion loss of the available circulators. The promise of increased stability with only a slight increase in the over-all system noise temperature led to the choice of the negative-resistance up-converter mode of operation.

Silicon mesa varactor diodes with 1 kMc Q's of 60 to 70* were available. These diodes, including the cartridge, have a zero bias capacity of 1.8 to 2.1 $\mu\mu$f. The series

*This was the Q of the wafer without encapsulation, measured at zero bias.

resistance typically lies between 1.7 and 2.4 ohms. A typical capacitance-voltage characteristic for these diodes is shown in Figure 3; the double-ended ceramic cartridge is shown in Figure 4.

The choice of the pump frequency was a compromise of several requirements. The availability of a stable klystron with sufficient power output to operate the two amplifiers and the frequency-stabilizing circuit; the gain-stability of the amplifier as represented by the proportion of negative-resistance gain and up-conversion gain required for the total paramp gain; and the optimum idler frequency for the minimum noise figure all had

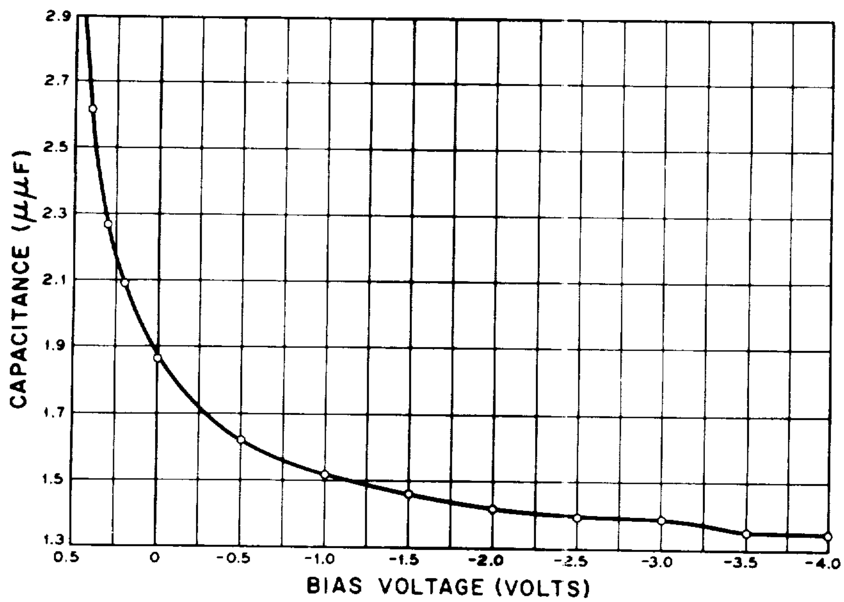

Figure 3—Capacitance vs. voltage for the silicon mesa varactor diode

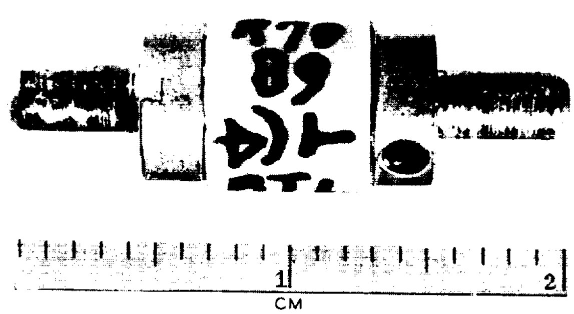

Figure 4—Typical encapsulated varactor diode

to be considered. The division of the required 60 db total gain between the parametric amplifier and the down-converter IF amplifier also entered into these considerations.

After study of the interaction of these various factors, it was decided that the experimental system should operate under the following conditions. The pump frequency would be 13.225 kMc. The required pump power could be met with a 3-db margin by using the Varian VA-92-C reflex klystron. For the 2390-Mc input frequency the idler or output frequency of the paramp became 10.835 kMc. The paramp was assigned 23 db of the total 60 db required gain. The up-conversion gain for the chosen idler frequency was 6.5 db. Thus 16.5 db of negative-resistance gain was required. The Sylvania coaxial isolator* provided 0.4 db insertion loss with 24 db isolation over the required bandwidth at 2390 Mc. Under these conditions the reflection coefficient (power) at the isolator input was 0.17. The antenna system return loss was greater than 30 db. An amplifier gain variation of less than 0.03 db resulted from the variation of antenna match.

The remaining 37 db of gain had to be supplied by the down-converter mixer and the IF amplifier. The down-converter mixer was allowed a 12-db noise figure in the consideration of system operation; it was felt that the noise figure would not be greater than this value.

The parametric amplifier gain is sensitive not only to the antenna load variation, but also to the pump amplitude and frequency variation. The klystron chosen was a stable one; it was mounted in a heavy brass box with forced-air cooling from a shock-mounted blower, so that no vibration was transmitted to the tube. The cooling air was obtained from the antenna cab interior, which was kept within 5° of a nominal 76°F by two large heater-air-conditioning units. A stabilizing cavity with its feedback circuit was not used to stabilize the klystron because such a system requires the expenditure of additional pump power, and insufficient power was available after the requirements of the two amplifiers and the short-term frequency-stabilizing circuit were met. This system of long-term stabilization proved adequate, since the overall system gain varied less than 0.5 db over the time required for a balloon pass.

The receivers that follow the output of the parametric amplifier system operate over a narrow band centered at 70 Mc. It was necessary that the parametric amplifier system output be held at 70 Mc regardless of the possibility of rapid random variations in pump frequency. The Echo receiving system has two channels, one for each circular polarization that might be received. Essentially identical operation of both parametric amplifier channels was insured by use of the common pump source, which also makes possible the maintenance of relative RF phase throughout the complete RF and IF system.

*This isolator was a modified form of Sylvania model FD135P.

The frequency-stabilizing circuit shown in Figure 2 prevents a rapid frequency variation in the output of both channels. The pump power was divided equally between the two parametric amplifiers and the local oscillator mixer by a 3-db directional coupler. A second signal at 2320 Mc was supplied to the mixer by a modified crystal-controlled microwave radio transmitter* (100 mw of power available). The 5-mw output of this mixer at 10.905 kMc was used to supply the local oscillator power for the two balanced mixer down-converters. The local oscillator mixer was a gallium arsenide diode supplied by Bell Telephone Laboratories, Allentown, Pennsylvania.

The stabilization of the 70-Mc output frequency against rapid pump frequency variation was accomplished in the following manner. Considered at some instant, the pump frequency is

$$f_p = (13.225 + \delta) \text{ kMc}.$$

The output of the local oscillator mixer then becomes

$$f_{LO} = (13.225 + \delta - 2.320) = (10.905 + \delta) \text{ kMc}.$$

The output of the paramp for a 2.390 kMc input signal under the effect of the pump shift was

$$F_0 = 13.225 + \delta - 2.390 = (10.835 + \delta) \text{ kMc}.$$

The resulting frequencies were mixed in the down-converter mixer and the difference frequency was applied to the 70-Mc IF amplifier. This difference frequency was

$$F_{LO} - F_0 = 10.905 + \delta - 10.835 - \delta = 70 \text{ Mc}.$$

A similar result could have been obtained for a negative δ shift in pump frequency. Thus for small shifts in pump frequency the output of the system was maintained at 70 Mc. It is true that the frequency of the paramp idler output, 10.835 kMc, varied with δ as shown, but the 10.835-kMc circuits were relatively wide-band and little or no signal impairment resulted.

PARAMETRIC AMPLIFIER DESIGN

The design of the parametric amplifier was based on a combination of mathematical analysis and experimental design. The gain of a lower-sideband up-converter can be expressed in terms of a reflection coefficient at a suitably chosen point in the input transmission line as

*A Western Electric TDE microwave transmitter, Model SD-59409-02, was modified by retuning and elimination of the last doubler stage.

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$$PG = \frac{\omega_{-1}}{\omega_0}(1 - \rho\rho^*),$$

where ρ is the reflection coefficient, ω_{-1} is the idler or output frequency, and ω_0 is the signal or input frequency. The magnitude of the reflection coefficient can be determined for a given power gain. Seidel has shown (Reference 3) that the Smith chart may also be used to plot the reflection coefficient, and hence impedances, when this coefficient is greater than one. With the paramp operating at low gain (relatively narrow bandwidth), the reflection coefficient was experimentally measured at both the signal and idler frequencies and plotted on a Smith chart; from this plot the impedance elements necessary to increase the gain and bandwidth were determined.

The initial paramp gain was obtained in the following manner. The capacitance-voltage characteristic of the varactor diode (Figure 3 is typical) was measured at 100 kc; C_1 and C_0 were determined (Reference 4) from this characteristic. Since these diodes were operated in a self-bias condition, the forward limit of capacitance variation was arbitrarily taken at a diode voltage corresponding to 1 microampere of direct current. This then located the limit of reverse bias capacitance for sine wave pumping. The change in capacitance between these two values was taken as C_1, and the average of these two capacitance limits was taken as C_0.

Microwave circuit elements were designed to resonate C_0 in the waveguide at the idler frequency and in the coaxial circuit at the signal frequency. These elements also transformed the waveguide impedance, considered on a voltage-power basis (Reference 5), to impedance levels at the diode that were comparable to the diode reactance. Provision for tuning was incorporated in the microwave elements.

The noise figure of the paramp was measured continuously while the circuit impedances were changed to increase the gain and bandwidth. The noise figure was minimized as the gain and bandwidth were increased.

The details of the completed parametric amplifier are shown in Figure 5. The 2390-Mc input circuit consists of coaxial elements. The 10.835-kMc idler output circuit was constructed of 0.4- by 0.9-inch X-band waveguide. The pump circuit consists of 0.311- by 0.622-inch Ku-band and 0.4- by 0.9-inch X-band waveguide (internal dimension).

The varactor diode was placed across the center of the X-band waveguide with one end supported by the center conductor of the 23-ohm input line. This section of line also contains the pump and idler choke sections. The other end of the varactor was grounded to the waveguide wall. The 23-ohm coaxial line is connected in series with an 11-ohm coaxial line slightly less† than $\lambda/4$ in length at 2390 Mc. This 11-ohm line is in series with a length of 50-ohm line, followed by a 50-ohm shunt-shorted stub. The isolator is connected in series at this point through a length of 50-ohm coaxial line.

† Determined experimentally

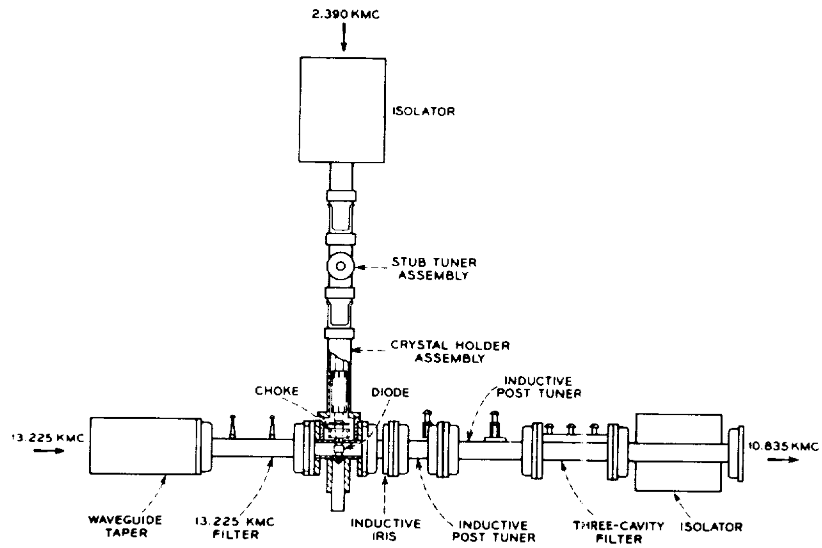

Figure 5—Assembly diagram of a single parametric amplifier

The choke in the center conductor of the 23-ohm coaxial line connected to the diode terminal prevents both the idler and pump signals from entering the coaxial input circuit. The radial line portion of this choke is resonant at 10.835 kMc. At the idler frequency the distance between this radial line section and the diode terminal at the waveguide wall is a quarter wavelength. The high impedance at the radial line terminals becomes a short circuit at the guide wall. The high-impedance coaxial line formed on the inside of the choke is resonant at the pump frequency, and thus provides an open circuit for the pump at the guide wall. The choke provides 26 db idler rejection and 30 db pump rejection.

The pump signal is fed from the Ku-band waveguide through a linear tapered section to the X-band guide containing the diode. Following the taper in the X-band guide is a two-cavity pump filter, which has a 60-Mc bandwidth at 13.225 kMc. The pump filter is placed with respect to the diode terminals so as to provide an inductive circuit element required by the idler circuit.

The output circuit at the idler frequency contains an inductive iris followed by two post tuners. By properly positioning these microwave elements, the remaining idler circuit elements are provided. The idler output passes through a three-cavity filter, with a 50-Mc bandwidth, and an isolator.*

The coaxial stub tuner and the idler output post tuners are adjustable, so that amplifier response can be adjusted in the event that wide ambient temperature changes

*Raytheon model 1HE4.

occur or in the event of diode replacement. The spare diodes are not identical with the characteristics of the in-service diodes.

The frequency response of the two parametric amplifiers constructed for the system is shown in Figure 6 for a gain of 23 db. The 3-db bandwidth is 15.5 Mc for the channel A amplifier and 21.5 Mc for the channel B amplifier (Figure 2). The noise figures for the separate paramps are 2.69 db (250°K) and 2.79 db (261°K) respectively, including the 0.4-db insertion loss associated with the coaxial input isolators. It is possible to achieve gains of 40 db by increasing the pump power. The band shape remains, but the bandwidth narrows to 2 Mc and the gain stability is extremely poor. A broad minimum noise figure exists for gains between 20 and 26 db, but above 26 db the increased pump level causes the dc short-circuited diode to draw current. A shorted dc diode mounting was chosen to simplify the mounting and to eliminate the need for separate stable bias supplies.

The down-converter mixer and the IF amplifier are of conventional design. The balanced mixer uses a "magic T" with a pair of 1N78MR diodes placed in broadband mountings in the conjugate arms. The mixer waveguide assembly is mounted directly on a five-tube 70-Mc IF amplifier. This amplifier has a 1-db bandwidth of 20 Mc and a gain of 51 db. The amplifier uses three WE 417A tubes, a WE 404A tube, and a WE 436A output tube. The down-converter mixer and the IF amplifier, when operated with a local oscillator drive sufficient to produce 0.5 milliampere diode current, have an overall gain of 38 db, a 1-db bandwidth of 20 Mc, and a noise figure of 12.5 db. The performance of the two units constructed was within 0.5 db of the above values.

The auxiliary mixer, which provides a frequency-stabilized local oscillator, employs a gallium arsenide diode. This diode is mounted across the center of a 0.4- by 0.9-inch X-band waveguide. One end of the diode is grounded to the guide wall, while the other end is held by the center conductor of the 23-ohm input coaxial line. The 2320-Mc signal from the modified crystal-controlled transmitter is coupled to this 23-ohm line through

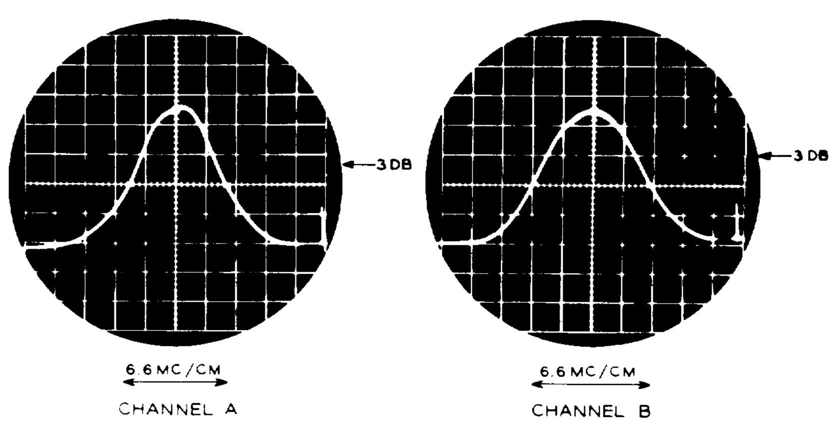

Figure 6—Parametric amplifier passband characteristic for channel A and channel B

a length of 50-ohm line and a shunt-shorted stub. The 23-ohm line contains a series choke of the type used in the parametric amplifier to block the pump frequency and the local oscillator output (10.905 kMc) from the coaxial input circuit. The pump power passes from the Ku-band waveguide through a linear taper to the X-band guide. A single-cavity filter is placed between the taper and the diode terminals, positioned so as to provide an open circuit across the diode at the local oscillator frequency (10.905 kMc). The tuning for the local oscillator circuit is provided by an inductive iris and a slide-screw tuner. The local oscillator output is taken through a narrow-band filter, centered at 10.905 kMc, and an isolator.* Sufficient output power was available to produce 1.2 milliamperes of current in each of the four 1N78 diodes in the two down-converter mixers.

INSTALLATION AND SYSTEM OPERATION

The parametric amplifiers, with the mixers, pump klystron, and their associated components, were mounted on the aluminum and magnesium frame pictured in Figures 7 and 8. The location of the various system parts are identified on these photographs.

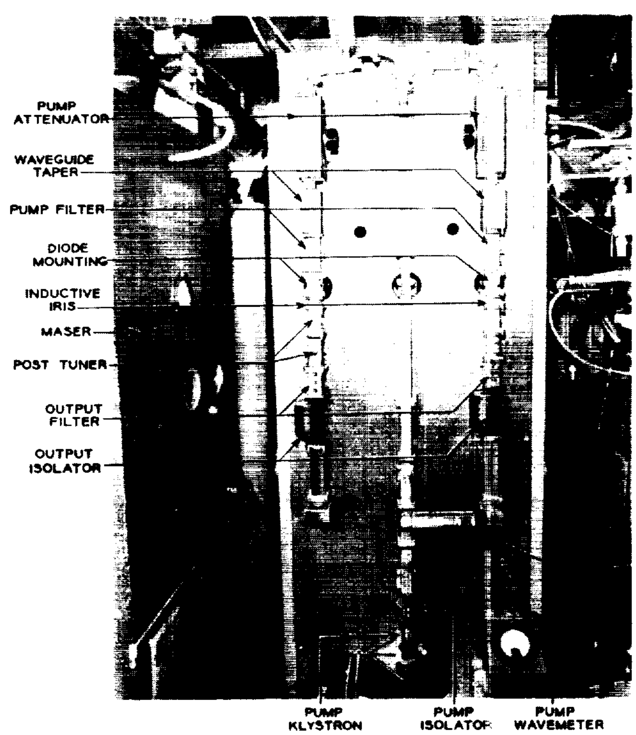

Figure 7—Dual parametric amplifiers mounted on support frame (side 1)

*An experimental Bell Telephone Laboratories isolator was used.

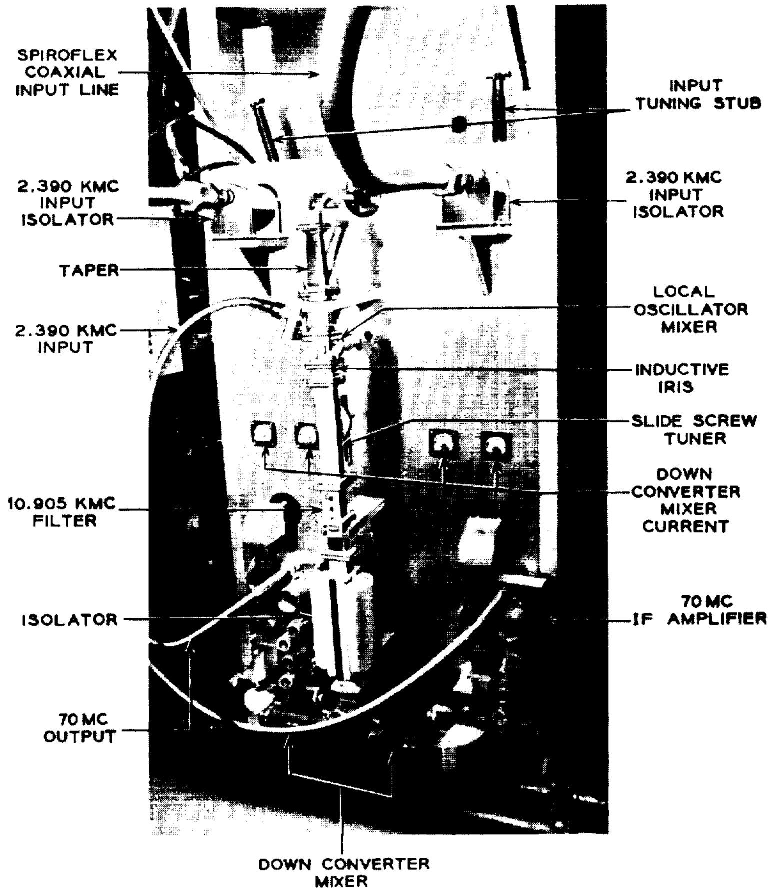

Figure 8—Dual parametric amplifiers mounted on support frame (side 2)

In order to simplify the operation of the amplifiers in the small confines of the antenna cab, controls and meters were grouped functionally on both sides of the frame. The pump klystron, frequency monitor circuit, pump level attenuators, and parametric amplifiers were grouped on one side of the frame. The opposite side of the frame contains the controls and meters associated with the local oscillator, the down-connector mixer, and the IF amplifiers.

After extensive tests were conducted in an antenna cab mock-up in the laboratory, the assembled system was moved to the actual antenna cab and bolted to the floor between the maser and the racks of test equipment. Although initially provision had been made on the parametric amplifier mounting frame for the power supplies, these components were mounted in a separate rack in the forward part of the cab with a 2320-Mc transmitter. Figures 9, 10, 11 and 12 indicate the position of the parts of the entire system within the antenna cab.

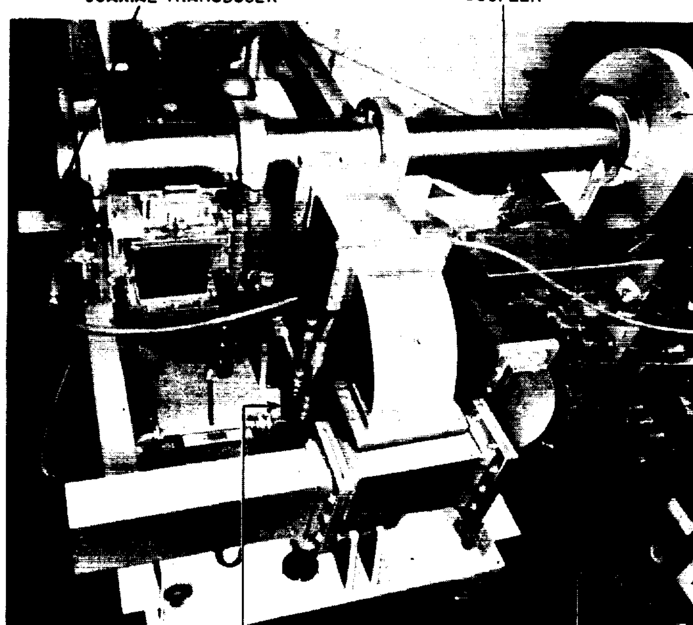

Figure 9—Relative position of parametric amplifier and maser in antenna cab

The inputs to the two channels of the parametric amplifier system were connected to waveguide-coaxial transducers at each polarization coupler with Styroflex semi-rigid coaxial line. The loss of each 6-foot coaxial cable run was 0.05 db. The transducers and coaxial cable runs were not permanently installed, since the maser was the primary receiving system. In the event of maser failure, the maser waveguide-coaxial transducers were disconnected from the polarization couplers and the parametric amplifier system connected with its transducers and coaxial cable. The arrangements of the transducers and cable run can be seen in Figures 8, 9, 10, and 12.

Prior to the launching of the Echo I satellite the parametric amplifier system was tested using signals generated locally from a swept 2390-Mc oscillator, a signal generator, and a precision attenuator or a noise lamp. Gain, frequency response, and noise figure measurements were made with these signals. Tests on the installed parametric amplifier system at paramp gains of 23 db showed the same bandwidth as was measured for the separate paramps, but the noise figure had increased. The noise figure of channel A was 2.97 db (283°K) as compared with a 2.69 db (250°K) and that of channel B was 3.07 db (297°K) as compared with 2.79 db (261°K). The increase in system noise figure over the individual amplifier noise figure was due to the effect of the down-converter mixers and the losses in the antenna lines and couplers.

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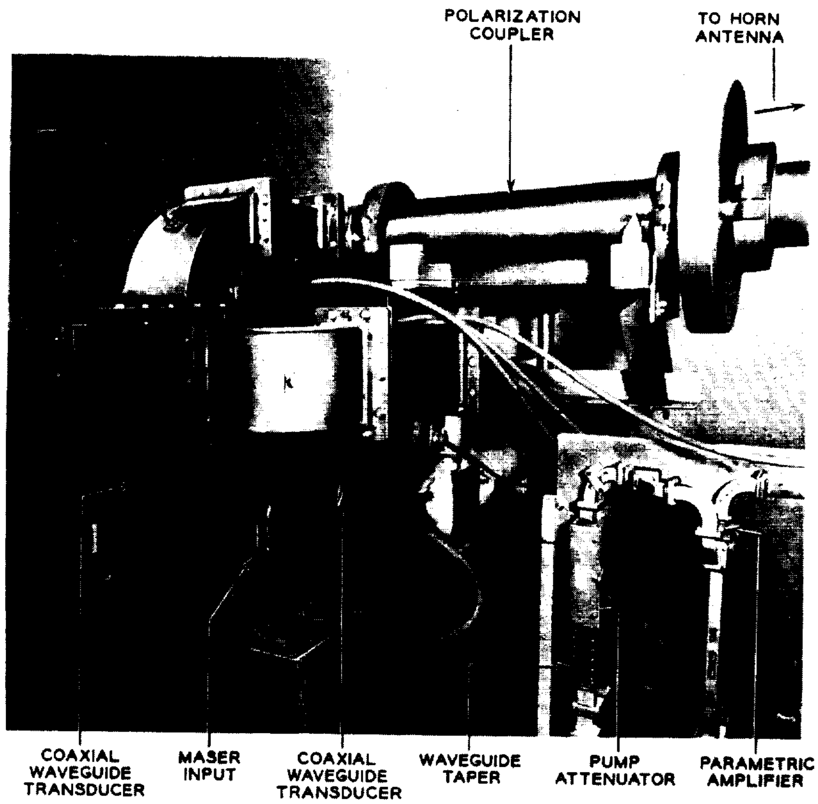

Figure 10—Position of parametric amplifiers and masers relative to the polarization coupler

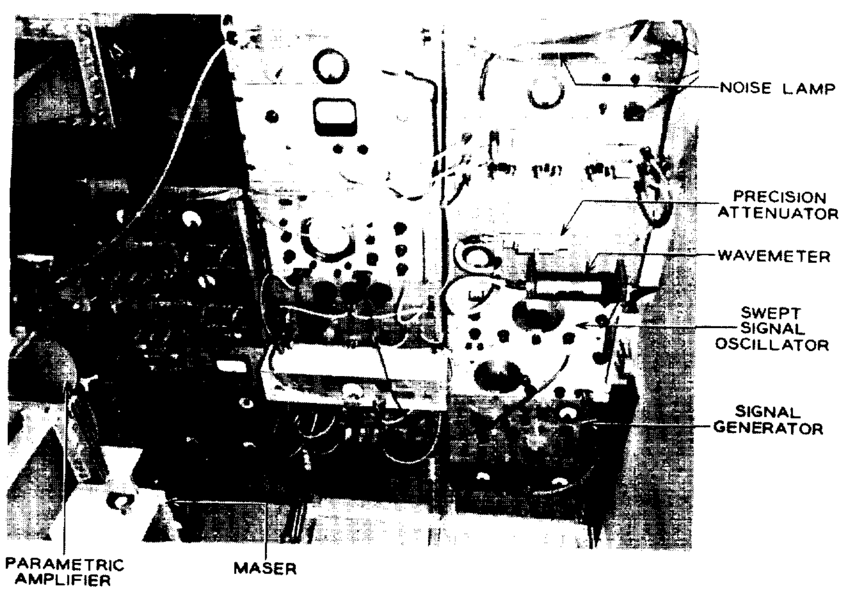

Figure 11—Test panel in the antenna cab

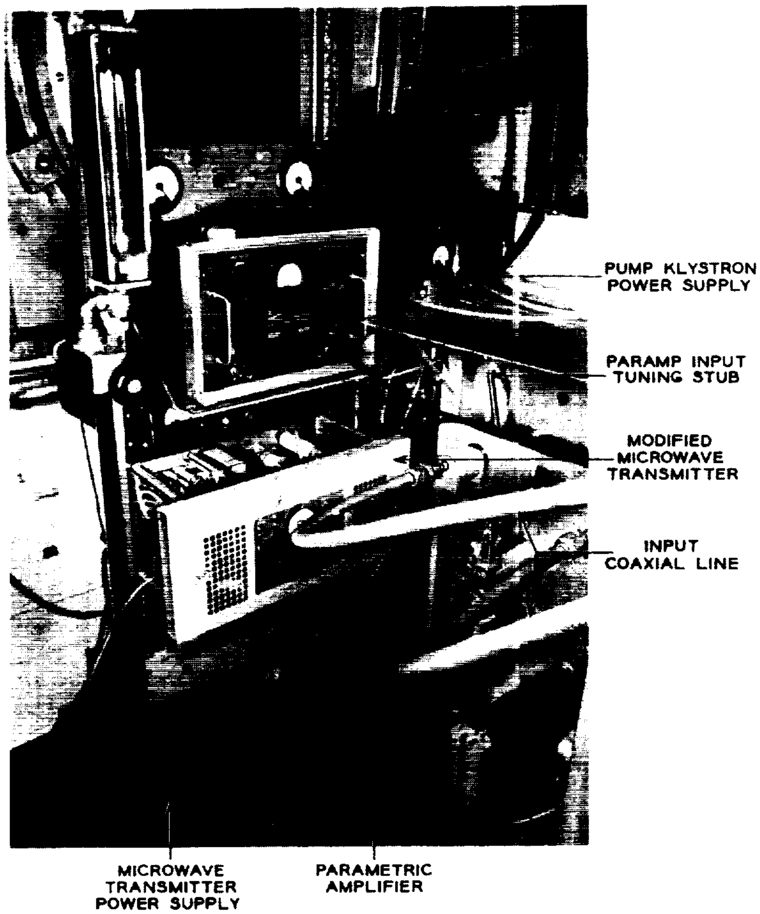

Figure 12—Parametric amplifier coaxial input lines, power supply mountings, and microwave transmitter

These results were confirmed by on-air operating tests conducted with signals received from the Jet Propulsion Laboratory facility at Goldstone Lake, California, by moon bounce. Figure 13 shows the noise received via the moon from Goldstone Lake with the parametric amplifier system as the antenna was scanned across the moon. While the noise increase was not large, it is quite plainly observable. Further tests indicated that the overall system using the parametric amplifiers had a minimum detectable signal level of -133 dbm over a 6 kc band.

The parametric amplifier system was put into use when the maser "iced up" 15 minutes prior to pass 93 of the satellite. But the parametric amplifiers were not previously on standby, and hence the pump klystron and all the tube circuits were "cold." Eight minutes before the pass the parametric amplifier circuits were energized. Signals were received from Goldstone Lake five minutes after the pass started, and the pass was completed satisfactorily. In the intervening 13 minutes, the maser was brought up to atmospheric pressure, vacuum seals were disconnected, and the parametric amplifier

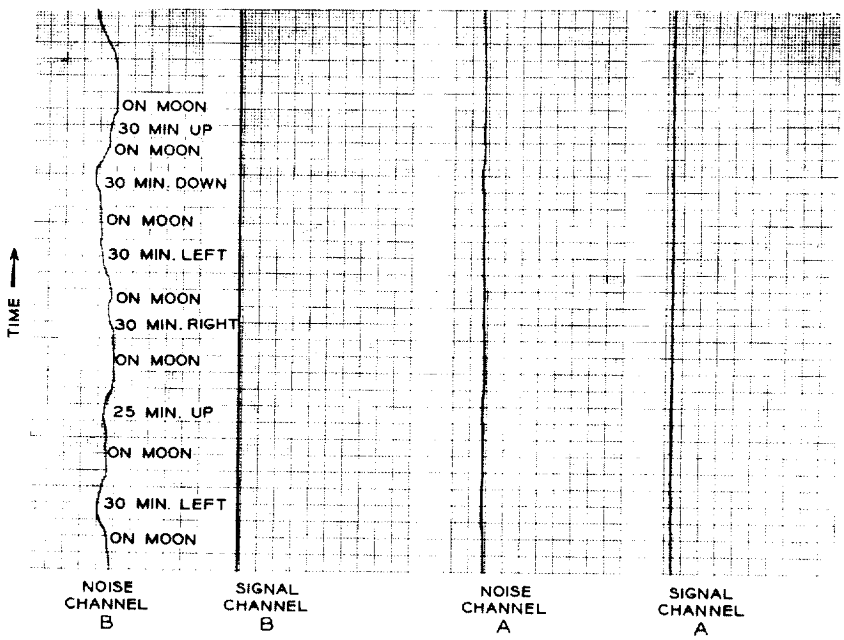

Figure 13—Noise signal received by the parametric amplifier system as the antenna scanned the moon

transducers and coaxial lines were installed in place of the maser units. The response of the parametric amplifier system was checked and minor tuning adjustments were made to compensate for the cold pump klystron. The parametric amplifiers continued in use throughout the rest of pass 93 and during pass 94.

The recorded received signal levels and input noise temperature for these passes are shown in Figures 14 and 15.

The parametric amplifiers system was operated on several later passes when the maser helium supply was low. In all instances the parametric amplifiers performed well and yielded the necessary information for the pass. The paramps were not generally able to detect the cross-polarized signals, since one polarization was 15 to 30 db below the main signal. The maser, on the other hand, with its lower noise temperature, was able to receive this component on almost all passes.

CONCLUSION

An experimental parametric amplifier receiving system has been shown to be adequate for communication experiments of the Echo type. The system is reliable and can be placed in operation in a short time. It is not subject to vacuum failures, "freeze-ups," or the need for expensive coolants. This system, of course, does not have the extremely

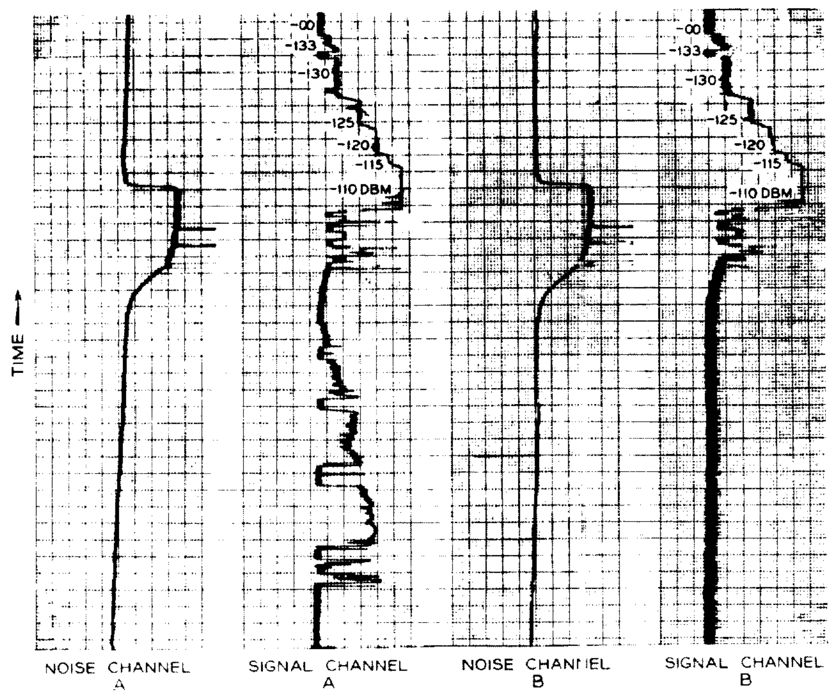

Figure 14—Recording of signal levels received by the parametric amplifier system from Goldstone Lake, pass 93

low noise temperature of the maser, although, if revised to include liquid nitrogen cooling, it could have a noise temperature as low as 40°K. In spite of the higher noise temperature, the parametric amplifier has been adequate for communication via balloon-type satellites.

ACKNOWLEDGMENTS

The author wishes to express appreciation to A. E. Bakanowski for supplying the varactor diodes, to W. M. Goodall and E. A. Ohm for their helpful criticism, and to J. E. LaVerne for assistance in the system assembly.

REFERENCES

1. Uenohara, M., and Seidel, H., "Project Echo – 961-Mc Lower-Sideband Up-Converter for Satellite-Tracking Radar," Bell System Tech. J. 40(4):1183-1205, July 1961; also NASA Technical Note D-1136, in publication, 1961.

2. Kurokawa, K., and Uenohara, M., "Minimum Noise Figure of the Variable-Capacitance Amplifier," Bell System Tech. J. 40(3):695-722, May 1961.

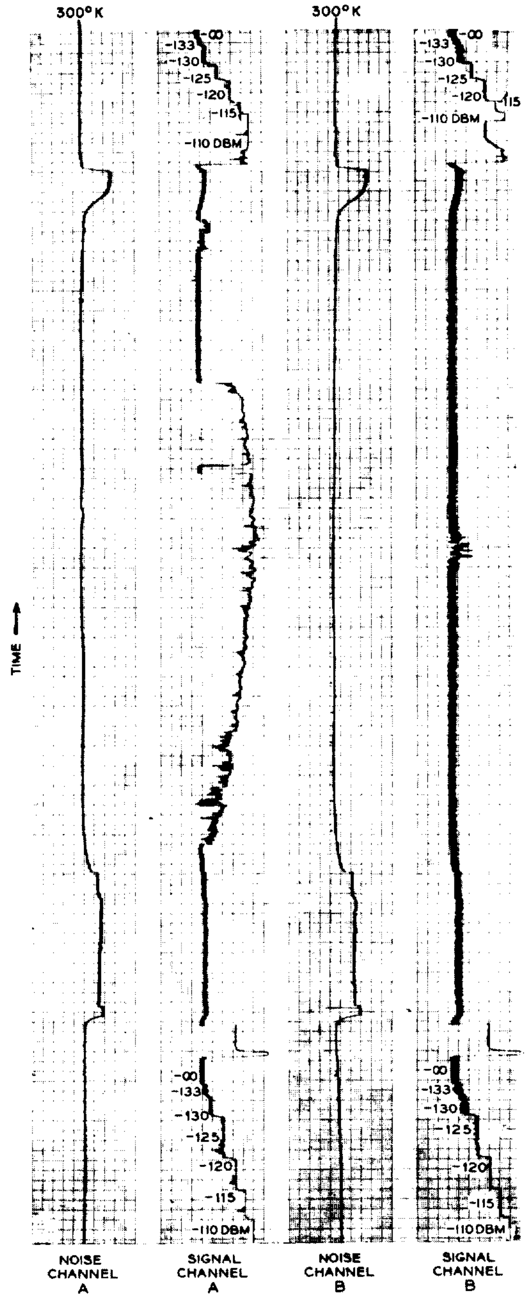

Figure 15—Recording of signal levels received by the parametric amplifier system from Goldstone Lake, pass 94

3. Seidel, H., unpublished manuscript.

4. Manley, J. M., and Rowe, H. E., "Some General Properties of Nonlinear Elements, Part I. General Energy Relations," Proc. I.R.E. 44(7):904-913, July 1956.

5. Southworth, G. C., "Principles and Applications of Wave-Guide Transmission," New York: D. Van Nostrand Co., 1950, p. 104.

NASA-Langley, 1961 D-1133