THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Electrical Engineering
Space Physics Research Laboratory and Electronic Defense Group

Progress Report No. 2

Period Covering February 1, 1959, to May 31, 1959

INSTRUMENTATION AND TRACKING OF IONOSPHERE PROBES

L. W. Orr P. G. Cath

UMRI Project 2816-3

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ABSTRACT

The progress on Task 3 for the interval from February 1, 1959, to May 31, 1959, includes further studies of the eutectic alloy, Cerrolow-117, used for thermal stabilization, and the development of a miniature version of the transistorized crystal oscillator. Further developments in the rf power amplifier for the nose-cone beacon are reported, and the required beacon power is calculated. A nose-cone antenna was designed, and construction is almost complete.

1. INTRODUCTION

This report reviews the developments under Task 3 for the period of from February 1, 1959, to May 31, 1959. It now appears that a two-frequency beacon can very likely be developed in time for the Wallops Island firings. In view of this, the frequency stability requirement is relaxed to one part in 10^6, and temperature control of the crystal oscillator to within about 1°C will be more than adequate.

Cerrolow-117, the eutectic alloy chosen for thermal stabilization, was investigated further during the period. Although some unusual effects were noted, it appears that temperature can be controlled to well within 1° at about 47°C. Using the heat-of-fusion method, a thermally stabilized package using a miniaturized version of the crystal oscillator at 36.9 Mc was developed. A 36.9-Mc transistorized power amplifier was developed in breadboard form, and work is now in progress on a frequency quadrupler circuit to furnish power at 147.6 Mc.

Power outputs of 100 milliwatts at 36.9 Mc and 10 milliwatts at 147.6 Mc are planned for the beacon. These are shown to be capable of furnishing signals at the ground station of more than 30 db in excess of the minimum needed for tracking throughout the entire coasting period of the flight.

In cooperation with Mr. Victor Richards of BRL, a two-frequency beacon antenna has been designed. Construction of a model suitable for field testing is almost complete.

2. PERSONNEL

Name	Title	Time
Lyman W. Orr	Task Engineer	Full-Time
Pieter G. Cath	Graduate Research Assistant	Part-Time
Wilbur Nelson	Technician	Part-Time
Nelson W. Spencer	Project Supervisor	Part-Time

3. MEETINGS AND REPORTS

On April 8, 1959, N. W. Spencer, F. F. Fischbach, and L. W. Orr visited the Ballistics Research Laboratories to discuss Task 3 with W. Berning, G. DeBey, V. Richard, and K. Patterson.

Progress Report No. 1 by L. W. Orr and P. G. Cath was issued in February, 1959.

4. THERMAL STABILIZATION

The method for satisfying the original stringent frequency stability requirements for the nose-cone beacon consists in the choice of a low-coefficient quartz crystal and a method of temperature stabilization. For present purposes, the heat-of-fusion method previously reported[1] still appears to be the most suitable, and will be used even though the stability requirements are not as severe for the two-frequency beacon as for a single frequency.

Cerrolow-117, the eutectic alloy chosen for thermal stabilization, has a heat of fusion of 3.3 cal. gm^{-1} (6 Btu/lb) and a melting point of 47°C (117°F). Certain peculiarities were noted in the behavior of the melting point, and this has been further investigated during the report period. Samples of approximately 50 grams were placed in glass bottles with a thermistor supported in the middle of each sample. Thermal cycling was performed by suspending the bottles in an oven at 75°C for the heating cycle and subsequently in the room at 30°C for the cooling cycle. Temperature records were taken on a slowed down Sanborn recorder using the circuit previously reported.[1]

The initial melting temperature appears to be a function of the <u>time lapse</u>. This is defined as the interval from previous freezing after a <u>complete</u> melt until the beginning of the new melt cycle. When the alloy sample is brought to a complete melt and then cooled, the temperature variation is as shown in Fig. 1(a) for a 20-minute time lapse, and (b) for a 20-hour time lapse. The different behavior is due to an obscure* effect in which the alloy appears to become reconstituted slowly at room temperature. In cooling from a complete melt, the alloy supercools to about 46°C. The temperature rises slightly as freezing begins. The freezing temperature is typically about 0.3° below the initial melting temperature, as indicated in Fig. 1.

*A possible explanation offered by the Department of Metallurgical Engineering is that the rise in initial melting temperature with increasing time lapse may be due to dissolved hydrogen produced by reduction of moisture slowly absorbed by the solid alloy at room temperature.

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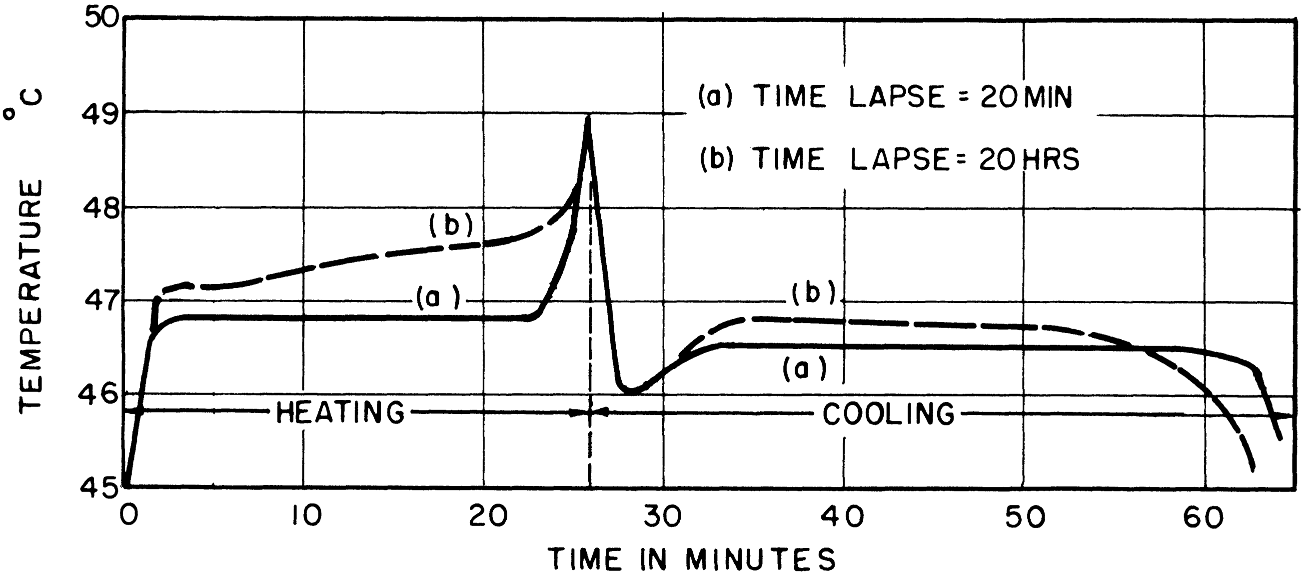

FIG. 1 TEMPERATURE VARIATION OF CERROLOW-117 FOR COMPLETE MELTING

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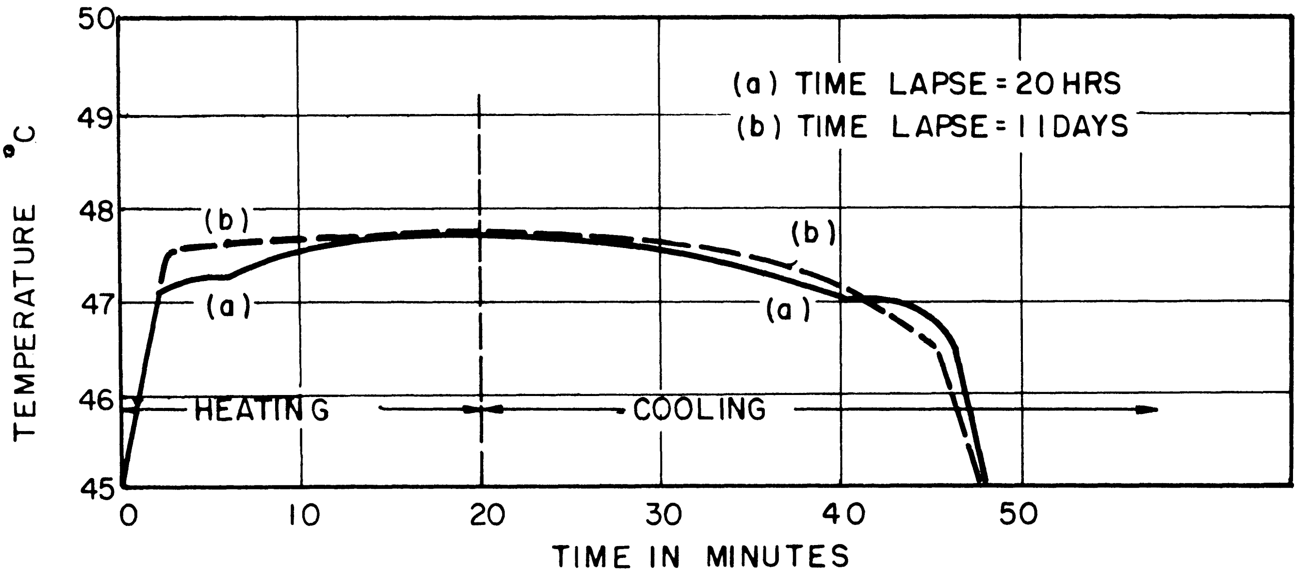

FIG. 2 TEMPERATURE VARIATION OF CERROLOW-117 FOR PARTIAL MELTING

When the alloy is cooled after partial melting, as in Fig. 2, supercooling is absent, and initial freezing takes place at the same temperature as the melting temperature late in the heating cycle. Here again there is a difference between melting temperature for a time lapse of (a) 20 hours and (b) 11 days. After running curve (b), the curve was re-run on the same sample after a 10-minute interval, and had a behavior essentially identical with the original (b) curve. Thus it appears that, to spoil the reconstitution, a complete melt and a temperature rise above 48°C is required.

This is interesting information, since it is planned to design the temperature-stabilizing unit in such a way as to prevent complete melting of the alloy at any time during the flight of the beacon. To obtain a temperature schedule such as shown in Fig. 2(b), i.e., stabilization to a few tenths of a degree, it is only necessary to use precautions not to melt the alloy completely in the final structure during the week or so prior to firing.

Irregular temperature behavior could possibly be due to a departure from the eutectic composition which might easily exist in the commercial alloy. A large sample of the alloy was therefore "purified" by five stages of recrystallization. The final pure liquid was called sample A. The crystal residues were lumped together as sample B. Simultaneous runs on A and B were made using a two-channel recorder. Time lapses and thermal cycling included all four conditions shown in Figs. 1 and 2. Differences in temperature behavior between A and B were minute and within experimental error. It was concluded (a) that the alloy furnished was very close to the true eutectic, and (b) that the irregular temperature behavior is not explicable on the basis of impure composition.

5. 36.9-MC OSCILLATOR

The oscillator circuit for the nose-cone beacon, as described in the previous report, has remained unchanged (see circuit "C" in Ref. 1). However, a much more compact assembly has been built to fit inside a temperature-stabilized case. This oscillator is shown in Fig. 3 beside its case. The actual flying model will be essentially the same, except for the transistor. The 2N502 transistors were found to be very fragile due to their physical construction. The 2N384 transistors (RCA) are much more rugged and they are recommended for use in the nose cone. As can be seen in Fig. 3, all oscillator components except the crystal are mounted on top of the mounting plate (1.150 x 0.950 in.).

The case is thermally stabilized by the heat-of-fusion method (see page 15 of Ref. 1). The chamber for the eutectic alloy (approximately 100 grams) is milled out in the bottom of the case as is shown in Fig. 4.

The oscillator was tested in this case in the following manner. The case was thermally insulated and heated by applying one watt of power to heaters

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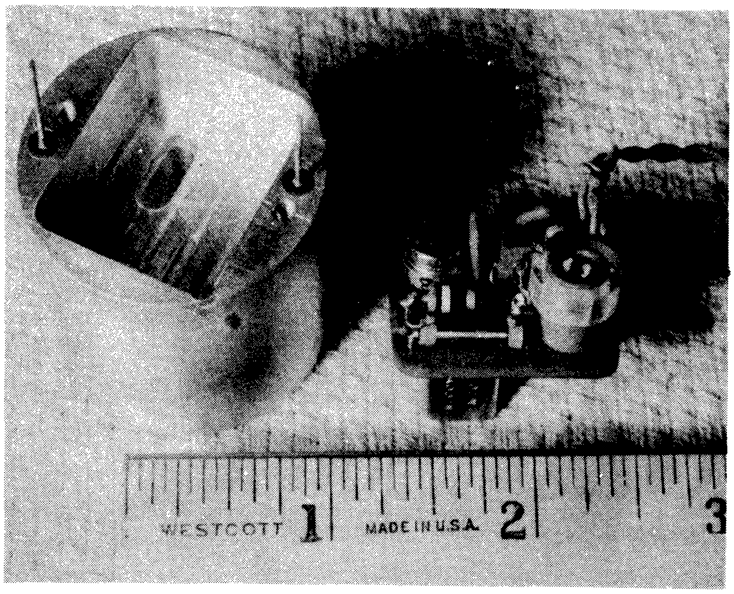

FIG. 3 OSCILLATOR WITH CASE

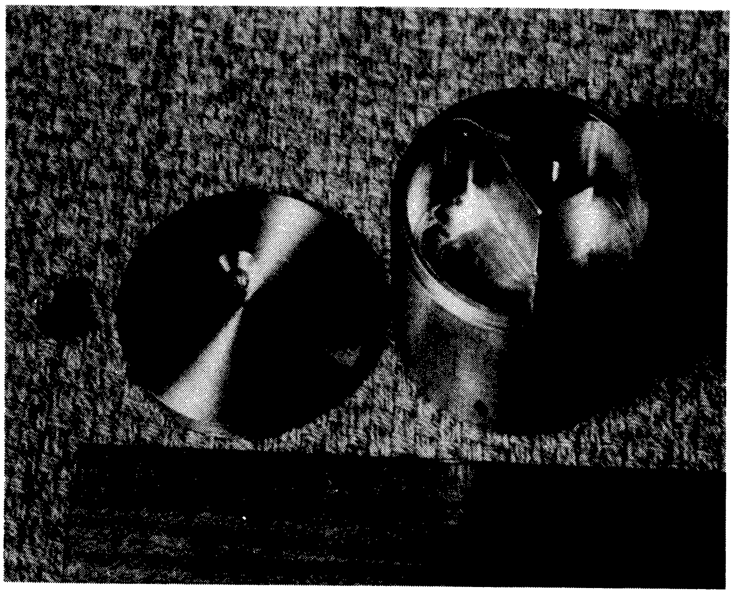

FIG. 4 BOTTOM VIEW OF CASE

imbedded in the aluminum case. After the alloy had melted, the heating element was turned off and the case was allowed to cool. During this test the oscillator was running and the frequency was observed. During the melting cycle the frequency stayed within 6 parts in 10^8 for a period of 30 minutes and during the cooling cycle it stayed within 3 parts in 10^9 for a period of 40 minutes. The frequency during the cooling cycle differed from that during the melting cycle by a small amount (2 parts in 10^7) due to a difference in temperature and the temperature coefficient of the particular crystal used. Better results will be obtained when the cooling cycle is started before all the alloy has melted.

An effort was also made to obtain crystals with an improved temperature coefficient. In the previous report (Ref. 1), it was pointed out that the turning temperature, i.e., the temperature at which the temperature coefficient is zero, for high-frequency crystals is difficult to control. The crystals are thin and it becomes virtually impossible to orient the crystal accurately enough during grinding. It was felt that fifth-harmonic crystals might be better than the third-harmonic crystals previously used, because they are thicker, and can therefore be oriented more accurately during manufacture. Three fifth-harmonic crystals were supplied by McCoy Electronics Company. All these have excellent temperature characteristics, and their turning points lie within a few degrees of 50°C. At 47°C, the melting point of the alloy, their temperature coefficients range from 2 to 4 parts in 10^8 per °C.

To obtain high Q, however, these fifth-harmonic crystals have to be larger in area than the third-harmonic crystals, and consequently they require a much larger crystal holder (McCoy M-2). With the fifth-harmonic crystals, the amount of feedback in the oscillator had to be increased, which indicates the larger series resistance of these units. Because it is planned to use a two-frequency probe (36.9 and 147.6 Mc), the requirement for frequency stability has been relaxed to 1 part in 10^6. For these reasons we plan to continue using the smaller third-harmonic crystals.

6. DESIGN OF CLASS C OUTPUT STAGES

The value of the collector load determines the maximum power that a transistor can deliver into the load and the efficiency with which it does this. The most important factors that must be considered when choosing a suitable load are the collector to base breakdown voltage (BV_{cbo}), the saturation voltage, and the collector dissipation.

Consider the circuit shown in Fig. 5. The peak voltage across R_L can never be greater than V_b. Therefore the power delivered to R_L can be at most $W_L = V_b^2/2R_L$.

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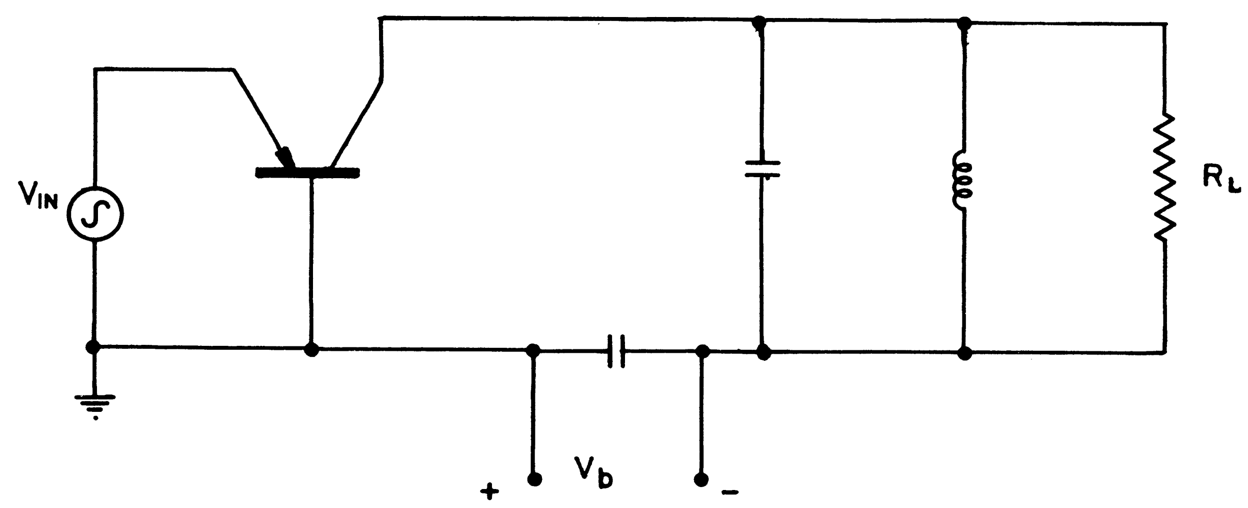

FIG. 5 CLASS C OUTPUT STAGE

W_L cannot be increased arbitrarily by increasing V_b because of the collector to base breakdown voltage (BV_{cbo}). The supply voltage V_b should not exceed approximately 1/2 BV_{cbo}. Neither can W_L be arbitrarily increased by decreasing the value of R_L. When R_L is made smaller, the collector efficiency decreases and quite soon the collector dissipation becomes a limiting factor. The cause of the drop in efficiency with a decrease of R_L lies in the saturation voltage of the transistor. To be able to draw a certain value of peak current I_{cp}, a minimum collector voltage V_{cmin} is needed. The d-c admittance of the transistor under this condition can be called $\sigma = I_{cp}/V_{cmin}$.

It can be shown that the product σR_L determines the maximum efficiency that can be obtained in class C operation (Ref. 2). This relationship is shown in Fig. 6. Obviously a compromise between power output and efficiency must be made when choosing a value for R_L.

Another transistor parameter that has to be considered is the emitter to base reverse breakdown voltage (BV_{eb}). This voltage is inherently low for a diffused base transistor because of the high impurity level in the base at the emitter junction. A typical value for BV_{eb} is 0.5-1.0 volt. When an attempt is made to increase the output power W_L by decreasing R_L, the driving voltage on the emitter has to be increased also. This means that, during the nonconducting part of the cycle, the emitter voltage may exceed BV_{eb}. Fortunately this breakdown is not very sharp, and it has been reported that the transistors suffer no damage when BV_{eb} is exceeded, provided that the total emitter dissipation is kept within bounds.

7. 36.9-MC POWER AMPLIFIER

So that the frequency of the oscillator will not be affected, it is desirable that the oscillator be only lightly loaded. Therefore a power amplifier was built with a power gain of 500 (= 27 db) to deliver 100 mw into a 50-Ω load. The circuit diagram of this amplifier is shown in Fig. 7. 2N384 transistors are used in the first two stages. These are RCA drift transistors (p-n-p, alloy). The overall efficiency is 35%.

The last stage uses a Texas Instrument 2N1143 (diffused base) transistor. It is in this stage that the design factors that were discussed above have to be considered to obtain the desired power output at a reasonable efficiency. The output coupling is adjusted so that the 50-Ω load is transformed to a load R_L = 1000 Ω at the collector. With a supply voltage of 16 volts, this stage delivers 100 mw with a collector efficiency of η = 50%. This value is in good agreement with Fig. 6. The values of the inductance and capacitance in the tank are chosen to give a loaded Q of approximately 20. The value of Q is not critical but it should not be too high because drift in component values might otherwise detune the stage. Too low a Q would cause insufficient rejection of higher harmonics.

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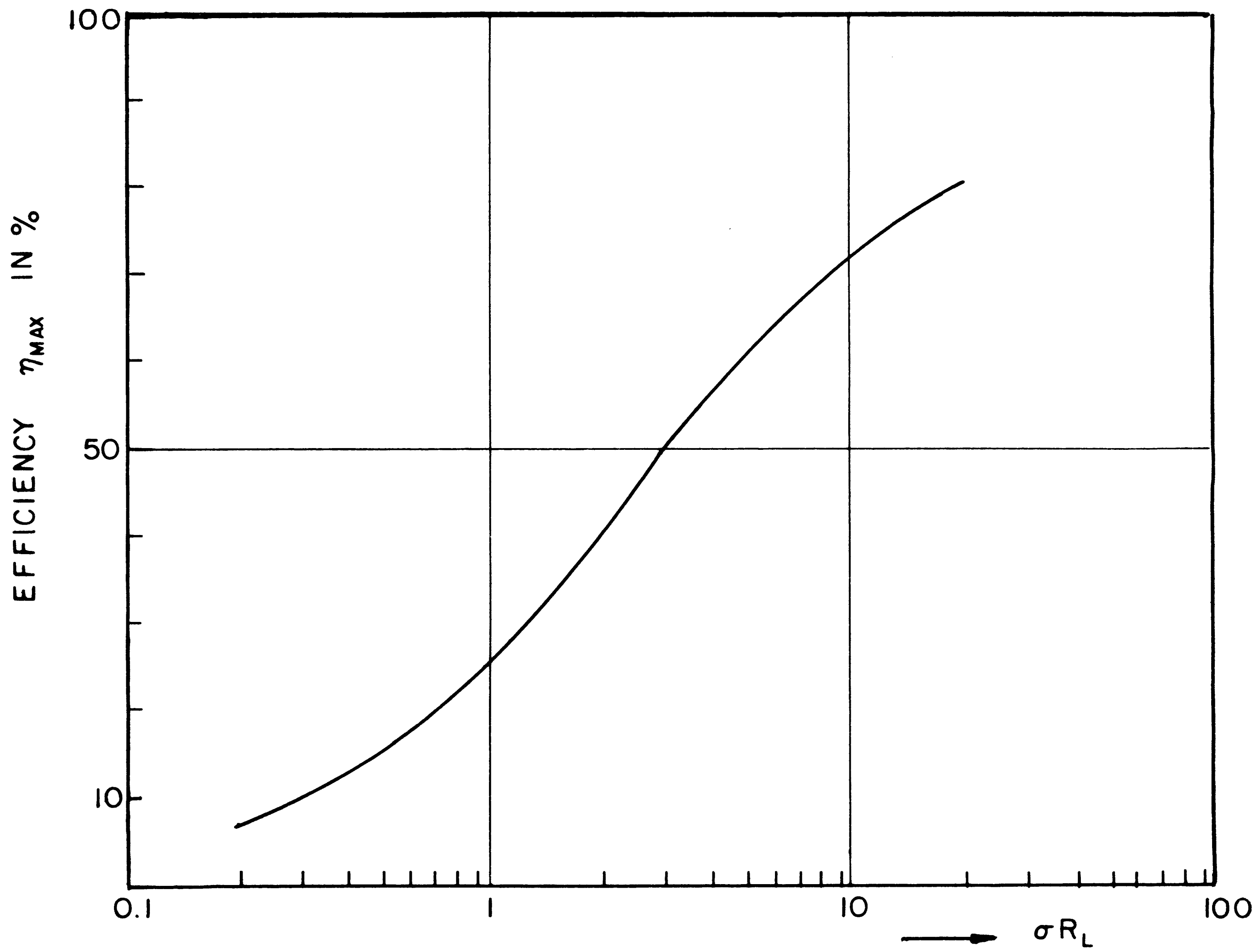

FIG. 6 MAXIMUM EFFICIENCY VS. LOAD

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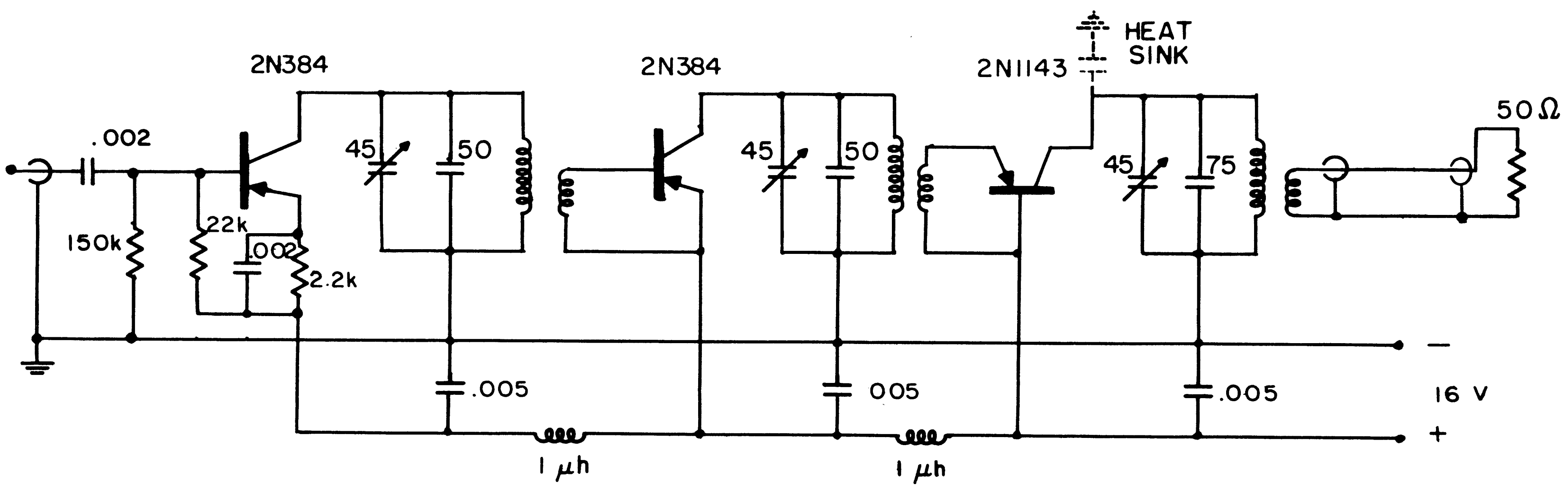

FIG. 7 36.9-MC POWER AMPLIFER

The collector of the 2N1143 is connected directly to the transistor case. An electrically insulated heat sink is used, which can be seen on the breadboard model shown in Fig. 8.

8. 147.6-MC AMPLIFIER

Work has started on a 147.6-Mc amplifier with two-frequency doubling stages. A 2N1143 transistor will be used for the output stage and measurements show that an output of 40 mw can be obtained at this frequency with an efficiency of approximately 30%. Work is in progress now to develop the two-frequency doublers.

9. REQUIRED TRANSMITTER POWER

The transmitter power required for the two-frequency nose-cone beacon depends on a number of factors including space attenuation, cosmic noise, antenna gain and efficiency, effective bandwidth of the ground receiver, and minimum signal-to-noise ratio required for phase lock of the tracking filter. A review of the various factors is presented here, and the margin of safety (gain margin) is calculated for the nominal values of power chosen for the beacon.

For free space propagation, the power received from the rocket-borne transmitter is given by

$$P_r = \frac{P_t \, G_t \, A_r}{4\pi D^2} = \frac{P_t \, G_t \, G_r \, c^2}{(4\pi DF)^2} \qquad (1)$$

where:

P_t is the transmitted power,
G_t and G_r are the antenna power gains,
A_r is the effective area of the receiver antenna
$A_r = G_r\lambda^2/4\pi = G_r c^2/4\pi F^2$,
D is the transmission path length,
F and λ are the frequency and wavelength of the transmission, and
c is the velocity of light.

A convenient formula for the space attenuation in decibels when using dipole antennas ($G_t = G_r = 1.6$ power gain) can be derived from (1):

$$\text{Space atten.} = 32.6 + 20\,(\log D + \log F) \text{ decibels} \quad , \qquad (2)$$

where D and F are expressed in miles and megacycles.

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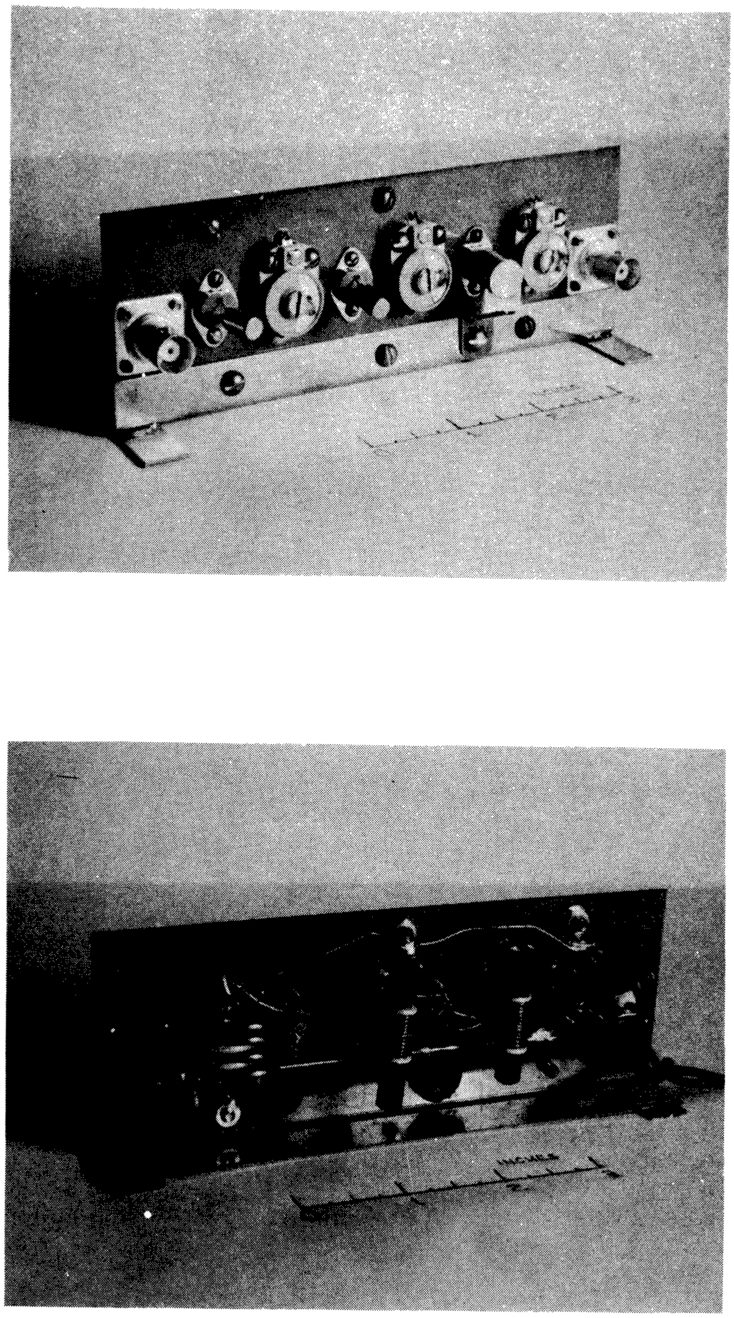


FIG. 8 FRONT AND REAR VIEWS

OF RF AMPLIFIER

(a) TRANSMITTER POWER REQUIRED AT 37 MC FOR D = 1000 MILES

At this frequency the cosmic noise level is so high that the noise figure of the receiver need not be considered. Because of the small size of the nose cone, a full-size loop cannot be used, and the inefficiency of the antenna must be considered. The tracking filter in the receiving system tracks with marginal locking with a phase jitter of 30° rms, and this requires a signal-to-noise ratio of 6 db. For tracking through the rapid acceleration phase of the rocket flight (maximum acceleration of 160 g), a tracking filter bandwidth of 25 cps at 37 Mc is required.

The space attenuation is first found from Eq. (2):

Space atten. = 32.6 + 20 (log 1000 + log 37)	=	124.0 db
Loss due to antenna inefficiency[3]	=	17.0 db
Total signal attenuation	=	141.0 db

Mean cosmic noise temperature[4] at 37 Mc	=	$T_n = 2 \times 10^4$ °K
Minimum tracking filter bandwidth	=	B = 25 cps
Boltzmann's constant	=	$k = 1.38 \times 10^{-23}$ joules/°K
Equivalent input noise power to receiver	=	$kT_nB = 7 \times 10^{-18}$ watt
Signal power required for marginal locking of tracking filter (6 db above noise)	=	$4kT_nB = 2.8 \times 10^{-17}$ watt

Transmitter power required is 141 db above 2.8×10^{-17} watt or

$$P_t = 3.5 \times 10^{-3} \text{ watt} \quad . \tag{3}$$

A nominal power of 100 milliwatts was suggested for the 37-Mc output. This gives a gain margin of 14.5 db. If the gain of the helical receiving antenna is now considered (approximately 8 db above dipole), a gain margin of 22 db is obtained.

(b) TRANSMITTER POWER REQUIRED AT 148 MC FOR D = 1000 MILES

At this frequency the cosmic background noise is much lower, and contributions due to internal receiver noise must be considered. A noise figure F = 2 (or 3 db) will be assumed.

Space atten. [Eq. (2)] = 32.6 + 20 (log 1000 + log 148)	=	136 db
Loss due to inefficiency of rocket-borne high-frequency loop antenna[3]	=	3 db
Total		139 db

Minimum tracking filter bandwidth[3] at 148 Mc, B = 50 cps
Receiver reference temperature T_r = 300°K
Equivalent noise power at receiver input due to internal receiver noise = $(F-1)kT_rB$ = 300kB

Mean cosmic noise temperature[4] at 148 Mc, $T_n \cong 700°K$
Cosmic noise power = kT_nB = 700kB
Equivalent receiver input noise power = 1000kB = 7.0×10^{-19} watt
Signal power for 30° jitter (S/N = 6 db) = 2.8×10^{-18} watt

Transmitter power required (139 db above 2.8×10^{-18}) = 2.2×10^{-4} watt

A nominal transmitter power of 10 milliwatts was suggested for the high-frequency unit. This would give a gain margin of 16.5 db. Allowing for the added gain of the ground receiving antenna, the gain margin increases to 24 db.

At both 37 Mc and 148 Mc an additional gain margin of 10 db can be realized. Tracking filter bandwidths of 25 and 50 cps are required during the rapid acceleration phase of the rocket flight, but during the coasting period, these bandwidths may be reduced to 2.5 and 5.0 cps since acceleration will then drop to one g. This decrease in bandwidth gives a noise reduction of 10 db in both channels. Taking into account all factors, 100 mw at 37 Mc and 10 mw at 148 Mc result in gain margins of 32 and 34 db, respectively, at 1000 miles.

10. NOSE-CONE ANTENNA DESIGN

The nose-cone antenna for both frequencies is a trapezoidal loop as indicated in Fig. 9. Models were constructed of 1-in.-wide copper foil with a tuning capacitor placed across the upper gap. A BNC connector was placed at the center of the base leg.

Dimensions for the 37-Mc loop are limited by the interior dimensions of the nose cone. The model constructed for impedance measurements had a height a = 26.5 in., base width b = 5.2 in., and top width c = 2.6 in. The tuning capacitor required for resonance was C_t = 20 μμf. For voltage feed, an upper series matching capacitor C_m = 375 μμf gave a feed point impedance of 50 + j 0 ohms when connected with 50-ohm coaxial cable to the BNC connector as shown. To obtain a voltage standing wave ratio of 2.6:1 or less (1-db mismatch), a detuning of ± 0.1 Mc was allowed.

Dimensions for the 148-Mc loop are determined primarily by the minimum practical size of tuning capacitor. The model constructed for impedance measurements had a height a = 12.0 in., a base width b = 5.0 in., and top width c = 3.5 in. The tuning capacitor required for resonance was C_t = 1.1 μμf. For voltage feed, a series matching capacitor C_m = 25.4 μμf gave a feed point impedance of 50 + j 0 ohms. To obtain a VSWR of 2.6:1 or less (1-db mismatch) a detuning of about ± 0.7 Mc was allowed.

When the high-frequency antenna was mounted inside the low-frequency antenna in a symmetrical manner with the planes of the loops perpendicular, the an-

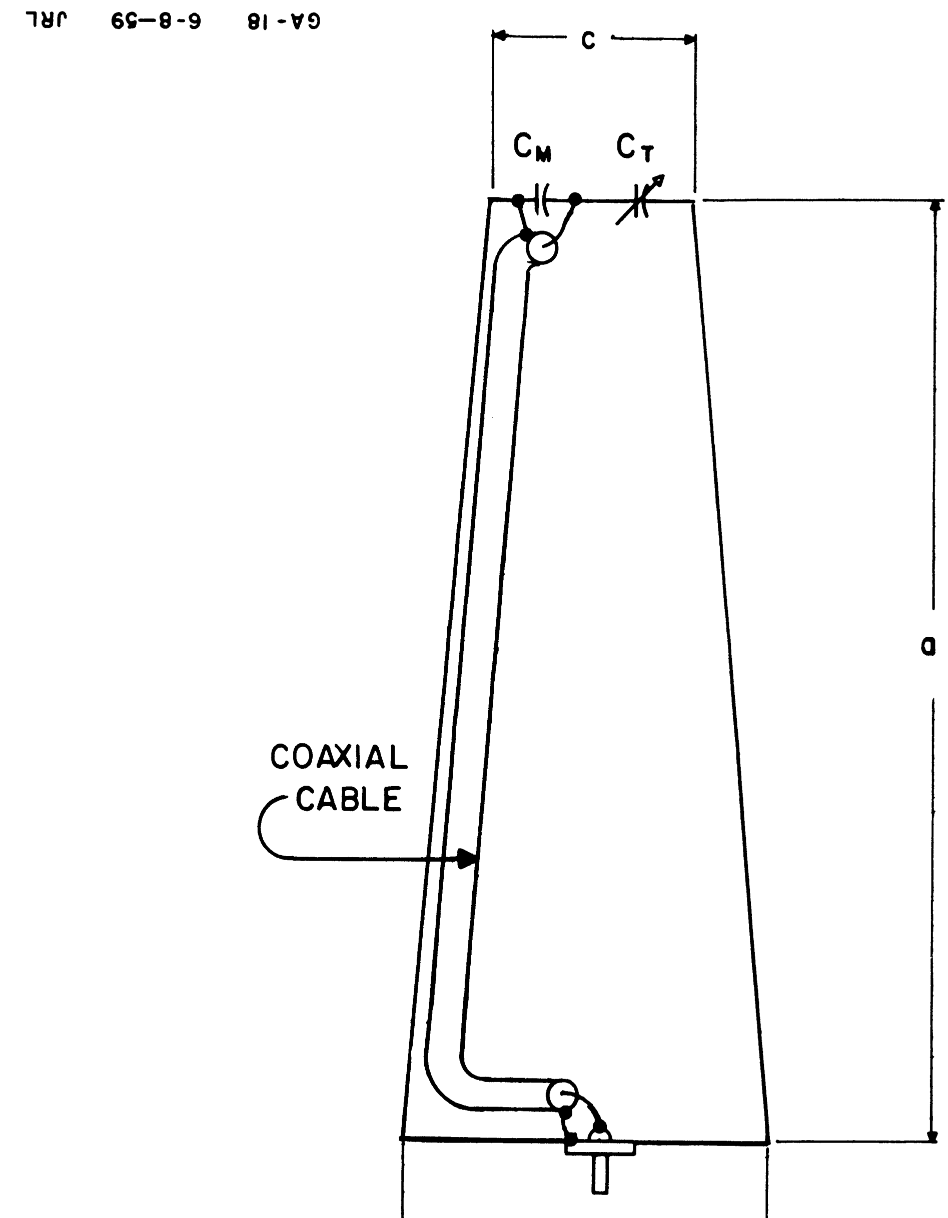


FIG. 9 LOOP ANTENNA WITH VOLTAGE FEED

tennas were found to be detuned only slightly (less than 0.2 Mc in either case), and the feed point impedance when retuned was unchanged.

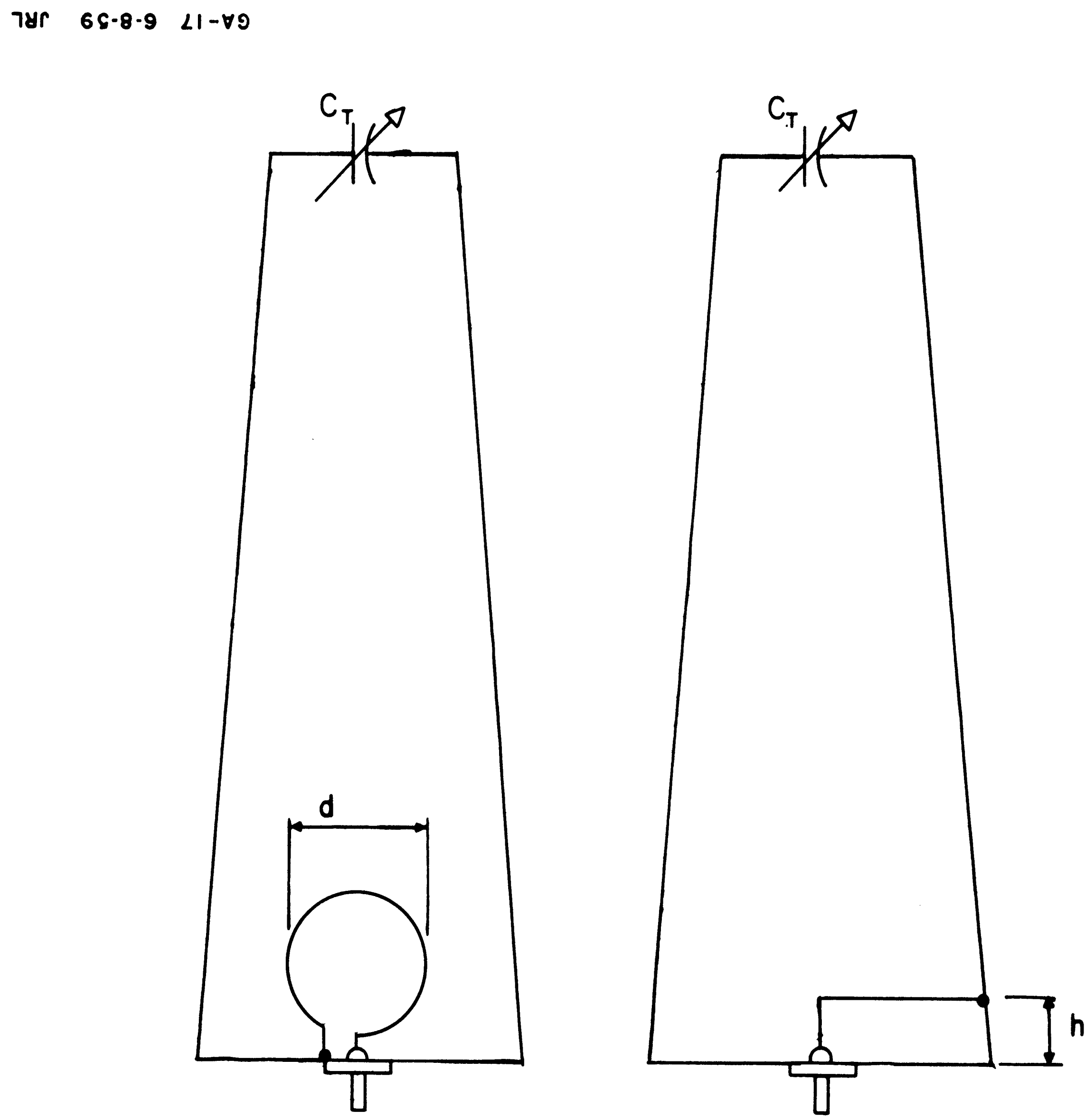
Tests were made to determine the required dimensions for current feed. Figure 10 shows two methods of current feed. These were both tried on the 148-Mc antenna model. To obtain a feed-point impedance of 50 + j 0 ohms for inductive coupling (Fig. 10a), a feed-loop diameter of 3.3 in. was required, and for side feed (Fig. 10b), a tap height h = 0.88 in. was needed.

Current feed methods are preferred because of their simplicity, but previous experience[3] with the inductive coupling loop has been that radiation efficiency is considerably below a corresponding antenna with voltage feed. This may be due to the fact that loop detuning is needed in the main antenna to compensate for the inherent inductance of the feed loop. Because of the lower inherent inductance of the side feed (Fig. 10b), it is felt that this method is worthy of further consideration.

It has been agreed that the mechanical design of the nose-cone antenna for the Wallops Island firings will be a self-supporting structure designed along the general lines of the 1950 Bumper Loop Antenna. Such a model has been designed and constructed, and is shown in Fig. 11. The height is 26.5 in. and the diameter of the base is 5.0 in. It is complete except for the addition of tuning capacitors and feed.

11. PROGRAM FOR NEXT INTERVAL

During the next interval, the development of the 147.6-Mc amplifier, and miniature packaging of this and the 36.9-Mc amplifier will be essentially completed. Assembly of a complete beacon package for thermal and vibration tests will be started. The nose-cone antenna will be completed and field-tested for radiation efficiency, with both voltage and current feed methods. Assembly of the ground-station equipment will commence pending delivery of the necessary GFE equipment.



(a) INDUCTIVE COUPLING

(b) SIDE FEED

FIG. 10 LOOP ANTENNA WITH CURRENT FEED

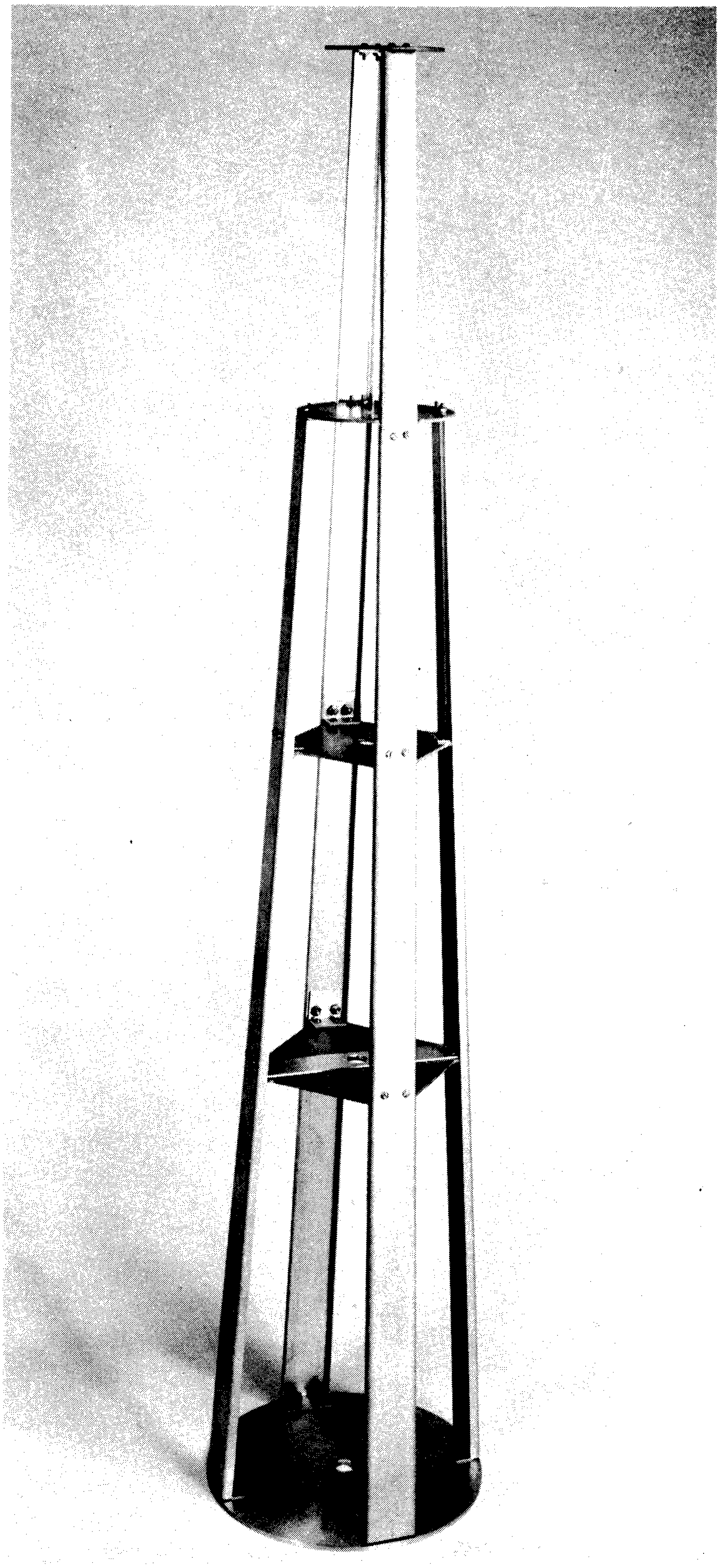


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FIG. 11 NOSE-CONE ANTENNA STRUCTURE

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2. Heyboer, J. P., Transmitting Valves, Philips Technical Library, Book VII, 1953.

3. Information obtained from BRL personnel.

4. Haddock, F. T., private communication.

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