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AN AIRBORNE RECEIVER FOR PULSED-LIGHT SIGNALS

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Civil Division, Commercial Litigation Branch

Subj: CHARLES E. PFUND V. UNITED STATES, COURT OF FEDERAL CLAIMS NOS. 276-87C AND 592-88C

Ref: (a) DOJ ltr 154-276-87/154-592-88 of 5 Jun 95

Encl: (1) NRL Memorandum Reports cover pages

1. Per reference (a), we have reviewed all the reports in the 5 June 1995 letter from Mr. Hunger and Mr. DiPietro.

2. The material contained in enclosure (1) describes measurements made relating to optical communication with submarines. The instruments and hardware used in the measurements is quite out of date and not in use currently. For example, the electronic circuits described employ vacuum tubes rather than solid state devices.

3. The measurements results do not reveal any operational details, but rather are descriptive of the instrument capabilities, the optical properties of water, and some atmospheric phenomenology.

4. None of the information contained in these reports requires any further protection.

5. In our opinion, every report itemized in reference (a) can be downgraded to UNCLASSIFIED and assigned a distribution statement A: Approved for public release; distribution unlimited.

CHARLES ROGERS
By direction

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ABSTRACT

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This report describes a photocell receiver which detects weak light pulses and converts them into audible notes which may be easily heard with headphones. The circuit constants are chosen so that the receiver operates with light pulses of less than 1 microsecond duration, each of which produces an oscillatory note, 1000-1200 cps, which has an on-period of 10 milliseconds.

The bandwidth of the receiver is approximately 7 kc to 2.5 Mc, which is well above the frequencies of ordinary mechanical vibrations. Operation on the ordinary photo-multiplier tube with a dynode voltage around 800 volts is possible under night conditions. At this dynode voltage the sensitivity at the input to the receiver is such that the input pulsed peak illumination required for triggering is only 0.005 microlumen/in.^{2}. The receiver operates on 115 volts at 400 cps.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

NRL Problem N03-02
Projects NR 562-000, Task NR 562-002,
and NE 120-713-2
BuShips No. S-1625

Manuscript submitted January 31, 1958

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AN AIRBORNE RECEIVER FOR PULSED LIGHT SIGNALS

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INTRODUCTION

Several previous reports (1-3) give detailed information on the transmission of ultraviolet light pulses from submerged transmitters to receivers placed aboard surface craft.

Since the radiant energy emerges from the submerged transmitter in a conical pattern and the maximum intensity is concentrated near the vertical axis, a limited operating range may be expected when a surface craft is used for receiver installation. As the optical paths are the same for two-way operating systems, it is reasonable to assume also that only very short ranges are possible for transmissions from surface craft to submerged receivers.

During HUKLANT operations in March 1954 (3), a number of tests were made with an ultraviolet light source on a submarine running at a keel depth of 150 feet, and with the receiver on a destroyer. The destroyer followed a zig-zag course which made a number of passes directly over the underwater transmitter. The best results showed that a surface range of about 200 yards was possible for this type of operation; this range is considered to be too small for tactical use.

As the detector unit of the receiver could be operated only 35 feet above the surface of the water, it may be readily understood from a previous report (3) why the range was so limited. Even after considering refractive and other effects it becomes very evident that the angle of the cone of radiant energy is too small for effective pickup along the surface.

For experiments designed to study the conical pattern of the radiated energy emerging from the water it was necessary to design a receiver which would operate in an aircraft up to 10,000 feet. The rack-mounted equipment and Tektronix oscilloscopes used in previous experiments for detection of the light pulses were too cumbersome for airborne operation. It was, therefore, decided to design and construct an airborne receiver that would convert video pulses (light trigger pulses) into suitable audio tones which could be heard distinctly and easily by an operator. This report is intended primarily to serve as an instruction manual for the airborne pulsed-light receiver.

DESIGN REQUIREMENTS

In the development of a receiver for airborne use the following requirements had to be considered:

operation on 115-volt 400-cycle lines,

portability,

resistance to vibration,

wide sensitivity range,

simplified panel control,

distinct recognition of signal.

[redacted]

The electronic circuit itself has the primary function of detecting a light pulse with time duration less than a microsecond and converting it into an amplified signal which can be heard as an audible tone. Since an audio frequency of approximately 1200 cps must be maintained for approximately 10 milliseconds to produce a suitable note for clear recognition, it was necessary to include the following circuit elements in the receiver:

photomultiplier detecting unit,

video or pulse amplifier,

triggered multivibrator,

audio oscillator,

multigrid gating tube,

one-stage audio amplifier.

The three units composing the complete receiver are illustrated by the block diagram of Fig. 1. Each of these units is housed separately in a suitable metal cabinet with good weight distribution and shock mounted to meet the standard requirements of aircraft service.

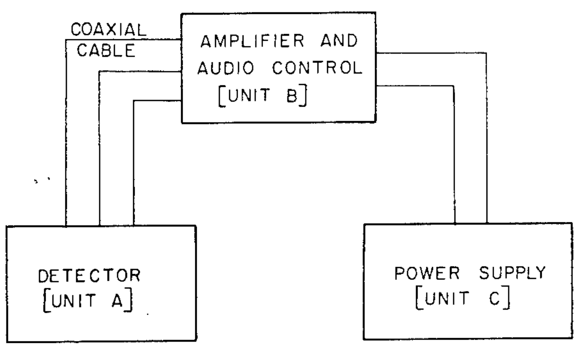

Fig. 1 - Block diagram of the receiver

Since the light detector itself is mounted in a separate unit, it can be placed at different locations in an aircraft. On the Navy P2V-7 plane a suitable installation was made in the photographic hatch where it is easy to use one or more phototubes with light-collector systems and removable optical filters.

The light pulse as detected by the photomultiplier tube produces a current pulse in the tube anode resistor which is sent by coaxial cable to any location in the plane where an amplifier and control may be conveniently placed. The amplifier is designed to build up the peak amplitude of the pulse so that the multivibrator will be triggered even by weak signals.

The multivibrator is adjusted manually to operate as a "one shot" square-wave generator which produces a positive gating pulse of about 10 milliseconds duration. This gating voltage is used in a mixer stage to pass about 12 cycles at the audible frequency produced by a continuously operating oscillator. This audio note is amplified through one stage and fed into the output circuit which includes one or more pairs of headphones.

Installation in various types of aircraft is made easier due to the fact that any arbitrary lengths may be chosen for the cables between the units. The input impedance into the amplifier, Unit B, is low (100 ohms) so that the coaxial cable connecting Unit A and B can be made as long as needed. However, because there is some line drop in the low-voltage heater circuits, it is best to use no more cable than necessary for a convenient installation. This is especially true for the cables leading from the power supply, Unit C.

CIRCUIT DESCRIPTION

The power supply and control panel are shown in Fig. 2, and a two-multiplier detector unit, used in some of the experiments, in Figs. 3 and 4. The open view in Fig. 3 shows how two 5819 photomultiplier tubes are arranged to provide wide-angle reception from the bottom of the plane. Optical filters may be added or removed from the apertures in the light-tight housing (Fig. 4).

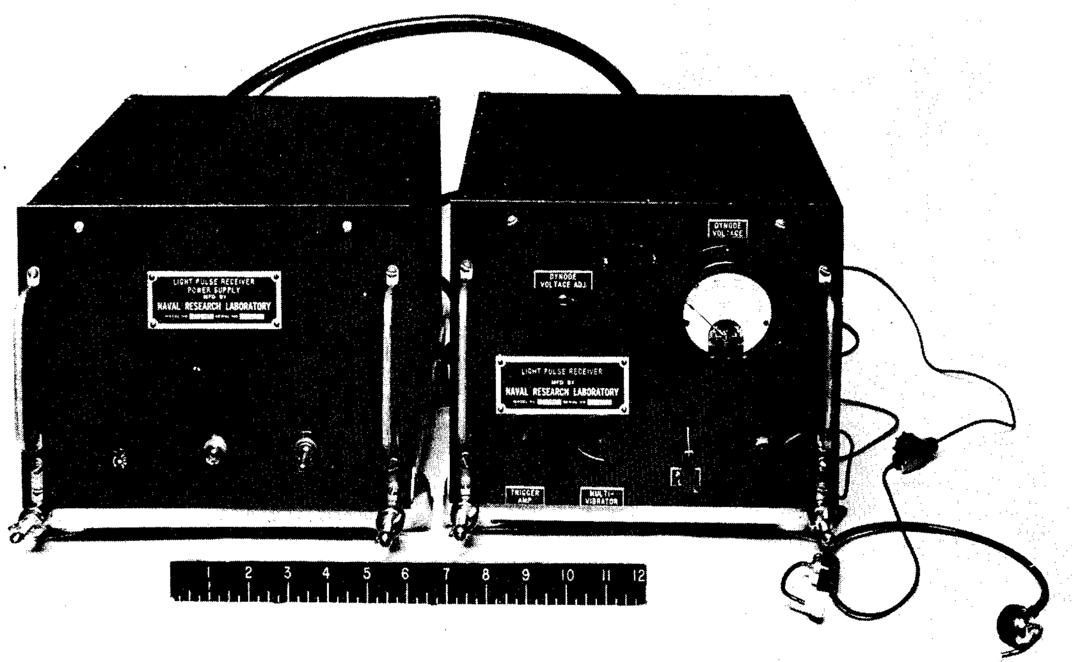

Fig. 2 - Control panel and power supply

The schematic diagram of the detector unit is shown in Fig. 5. It is essentially the same design as the detector described in an earlier report (4) except that the amplifier tube is omitted and the signal is fed directly from the photomultiplier anode into a cathode follower tube. This tube (Type 5654) serves as an impedance transformer and permits the signal to be transmitted through a 100-ohm coaxial line. In the twin-tube unit shown, the second 5819 tube has an identical dynode voltage divider circuit and the anodes of the

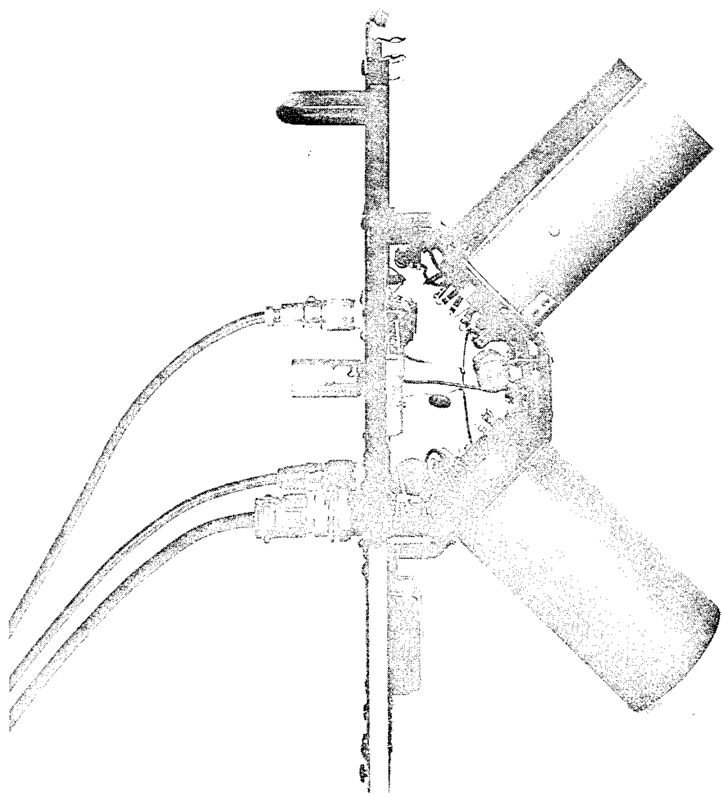

Fig. 3 - Detector unit using 5819 photomultiplier tubes

two multiplier tubes are simply connected together. The RC time constant of the circuit is low enough to handle pulse signals with frequency components up to around 2.5 Mc.

After transmission through the coaxial cable, the pulse signal is amplified through a video-type amplifier located at the input of the gating and audio unit (see Fig. 6). The three 5654 tubes are arranged and wired so that experimental series and shunt peaking coils may be inserted or removed depending upon the type of amplification needed in the strip. At present an RC amplifier is used where the load resistors R_L have an experimental value of 18 kilohms and the coupling capacitors have values from 82 to 250 $\mu\mu$farads.

After the signal is amplified, it is passed through a 6AC7 tube which acts as a phase splitter. When the output is taken from the cathode resistor of this tube the signal keeps the same phase but when taken from the plate circuit the signal is inverted. A switch located on the chassis makes it possible to select a positive pulse for the trigger amplifier tube when either an odd or even number of amplifier stages are used. From the plate of the 6AG7 trigger amplifier tube, the negative pulse is injected into the multivibrator though a diode (6AL5) which automatically decouples the trigger amplifier tube once the multivibrator is triggered.

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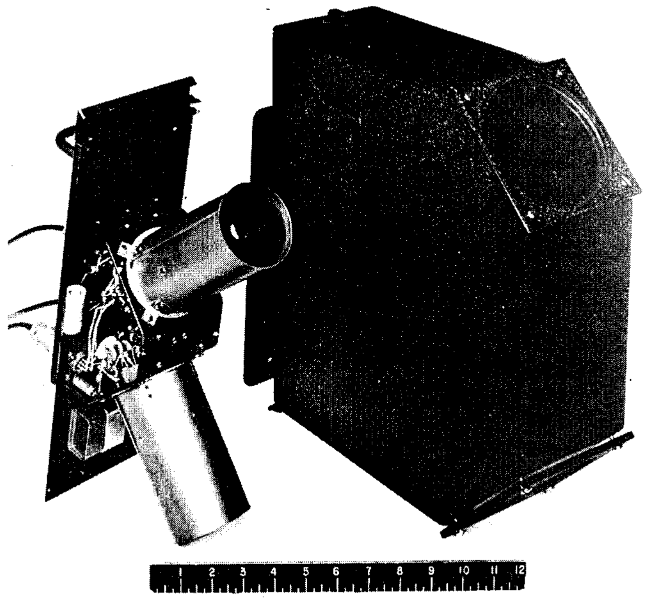

Fig. 4 - Detector unit with housing

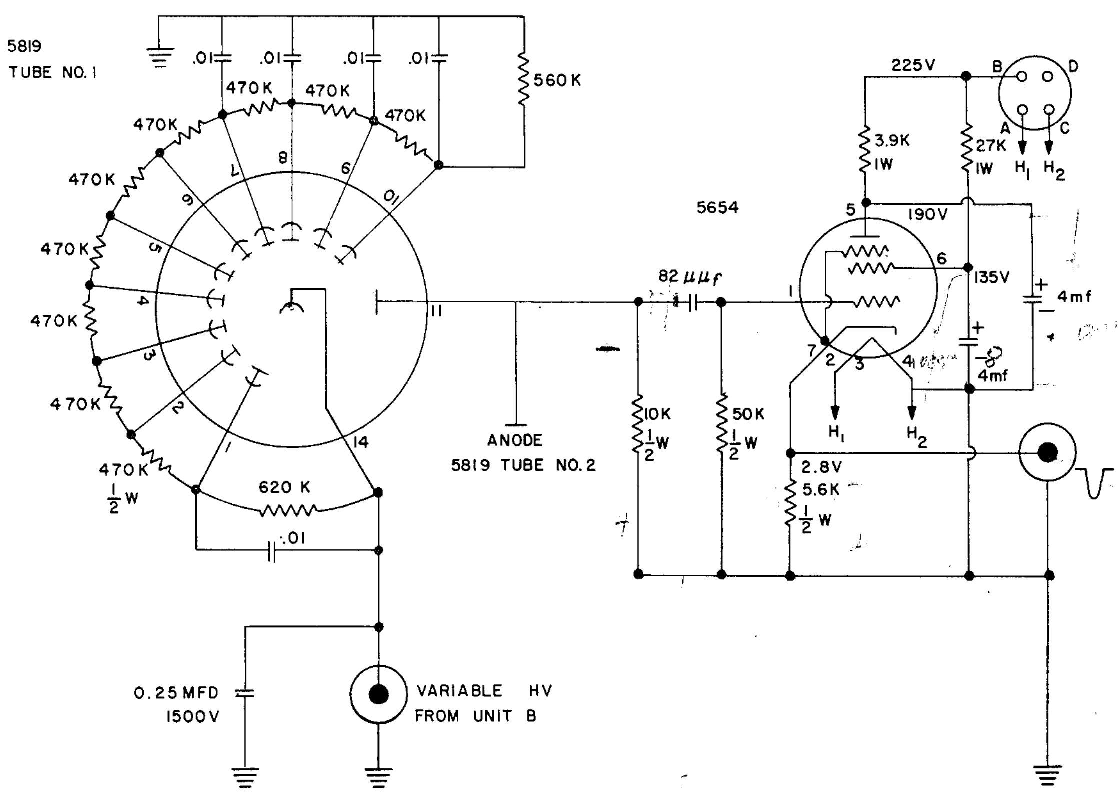

Fig. 5 - Schematic diagram of detector (Unit A)

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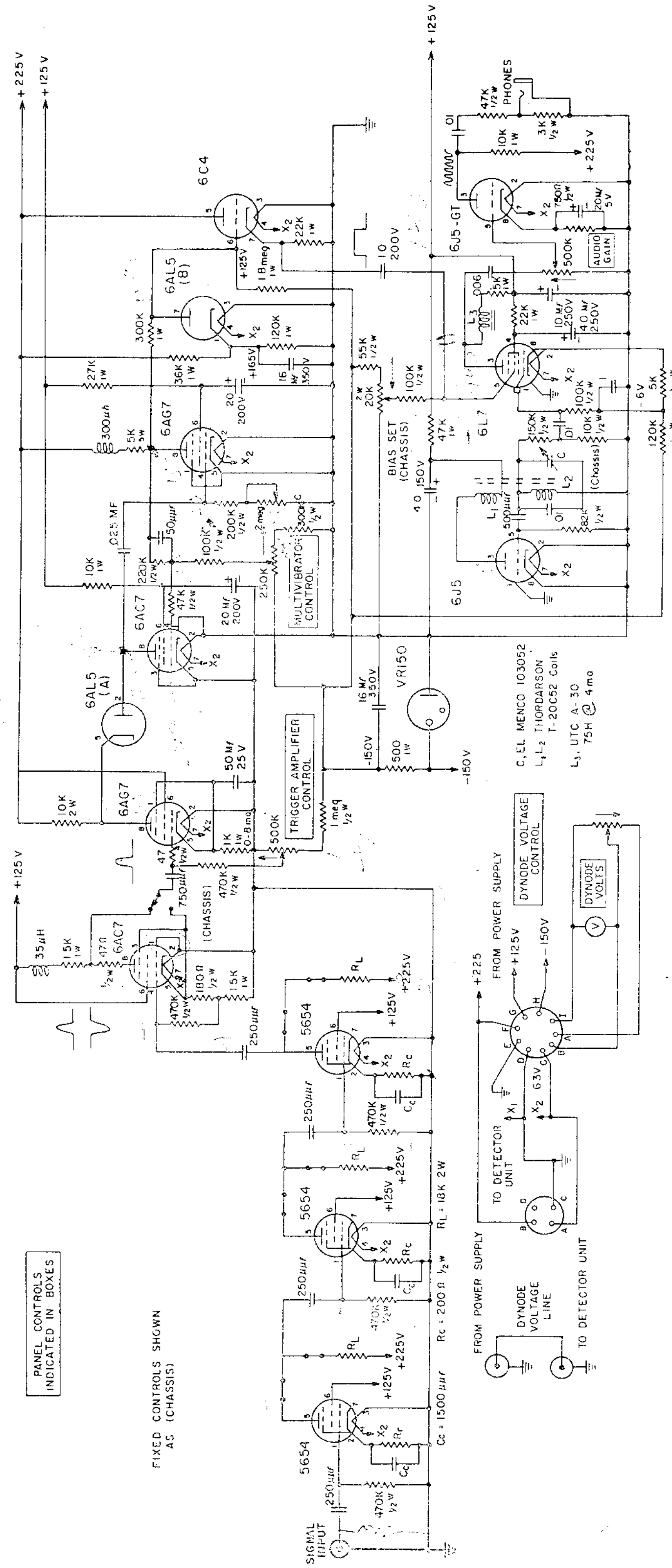

Fig. 6 - Schematic diagram of amplifier, gating, and audio circuits (Unit B)

A typical multivibrator circuit is used, the constants being chosen to give a positive rectangular pulse with a time duration of approximately 10 milliseconds at the plate output of the second tube (6AG7). This gating pulse is clipped by the second half of the 6AL5 diode and connected to the No. 3 grid of the 6L7 mixer tube through a cathode follower (6C4). A slight variation in the duration of the gating pulse may be made by adjusting the 2-megohm potentiometer located on the chassis. Otherwise the operation of the multivibrator is controlled by a single 250-kilohm potentiometer located on the front panel.

In the gating or mixer tube (6L7) the audio signal is applied continuously to the No. 1 grid, but a cutoff bias is applied to grid No. 3. This permits no audio to pass except when a positive gating pulse is injected from the cathode follower (6C4).

The audio-frequency sine-wave generator, which is tunable from 1000 to 1200 cycles, is designed around a single 6J5 tube. The grid coil is tuned in a grid plate type of oscillator by a screwdriver adjustment on the chassis. During flight, ordinarily only one setting is required. Proper output voltage is obtained by using a resistive divider across the grid coil and a capacitive coupling to the grid of the mixer tube. Plate and grid coils L_1 and L_2 are coupled together by mounting them on a closed core of only two or three laminations. Small coils from filter chokes serve very well for the purpose, and the oscillator has a good operating margin to allow for line voltage changes.

For the output stage a triode is used with a gain control in the grid circuit. The plate circuit is matched into a headset which is connected into the receiver by means of a plug and jack.

In Fig. 7 is shown a schematic diagram of the power supply. Four transformers constructed at NRL are used to supply the ac heating currents and the dc operating voltages. The high-voltage transformer T_1 is used in half-wave rectification to supply the dynode voltage to the photomultiplier tube in the detector unit. Instead of using a divider circuit in the high-voltage output, a potentiometer is used to vary the ac voltage across the primary of T_1. This potentiometer and a voltmeter are located on the control panel of Unit B. By adjusting the potentiometer across the primary it is possible to vary the rectified dynode voltage from zero to approximately 1200 volts. The calibration of the voltmeter on the panel was made with the proper resistive load across the high-voltage supply and a vacuum tube voltmeter was used to get the dynode voltage values.

As shown in Fig. 7 there are three other rectifier and filter supply circuits to give suitable bias and plate voltages. A conventional full-wave power supply is used to maintain the plate and screen voltages of +225 and +125 volts, respectively. For the biasing voltage (-150 volts) a half-wave rectifier is used from one side of the full-wave transformer T_3. This voltage is stabilized by a voltage regulator tube (VR150) located on the chassis of the amplifier, Unit B.

No special circuits were incorporated to stabilize the plate and screen voltages but this does not seriously affect the operation of the triggering circuits. The 115 volts supplied from a good inverter is sufficiently stable to insure good operation of the pulsed-light receiver if the line loading does not fluctuate more than 3 percent. Once the trigger amplifier and multivibrator controls are set, the loading of the receiver is practically constant even with different settings of the potentiometer that controls the dynode voltage.

The power required by the receiver is approximately 120 watts. Also, the receiver should always be operated on line voltages above 105 volts and below 122 volts, a line value of 115 volts being preferred. Both requirements are easily met at several convenient points in an aircraft.

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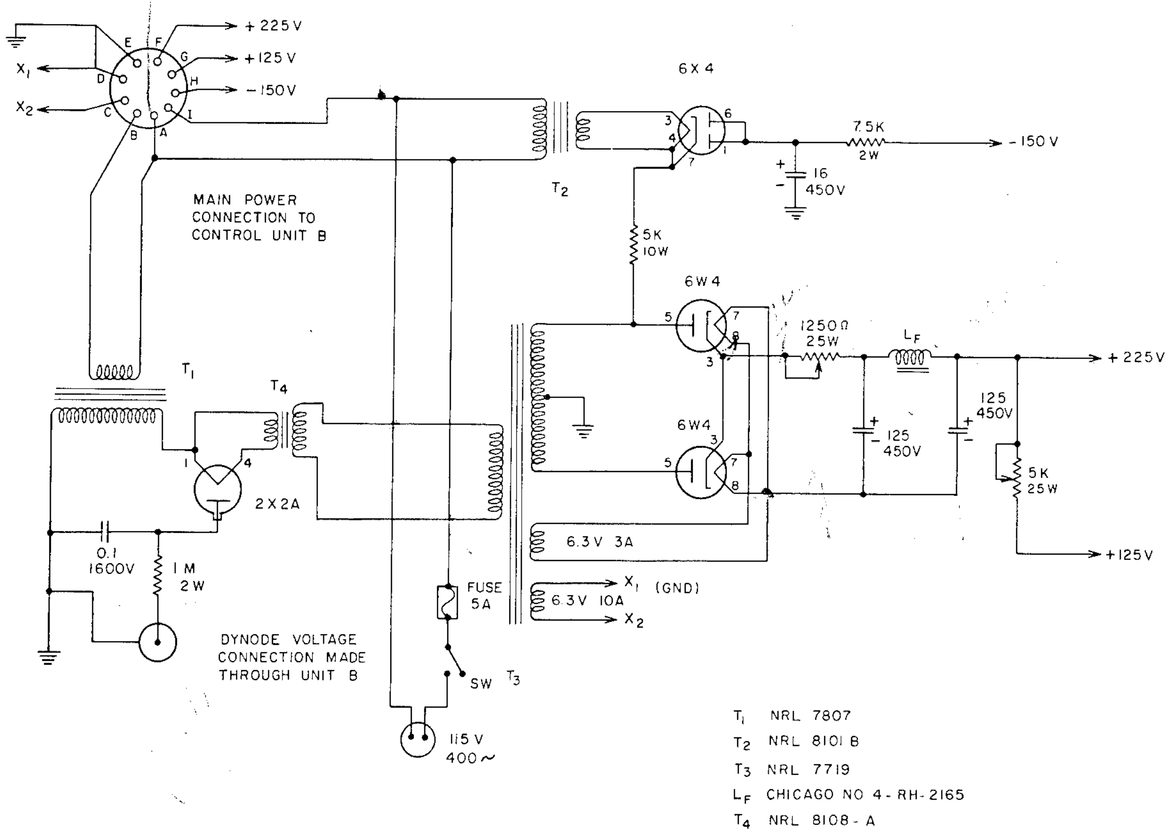

Fig. 7 - Schematic diagram of the 400-cycle power supply (Unit C)

OPTICAL SYSTEMS FOR THE PICKUP UNIT

Although the electronic circuit for the detector unit is complete in essential details no single type of pickup unit has been selected. To date, however, it has been established that one or more head-on photomultiplier tubes (Type 5819 or 6199) can be used to obtain different patterns of field coverage. No scanning or special pickup systems have been utilized since the main objective at the present time is to make range studies by having the airplane fly through the center line of the pulsed-energy cone at different altitudes. Thus it is possible to get a plot of threshold points which determine the periphery of the useful cone.

No optical devices were used in preliminary flights but the advantage of using some optical system may be readily demonstrated.

If a single photomultiplier tube is installed in an aircraft so that the cathode face is parallel to the surface of the water, the triggering energy E may be expressed by the equation

$$E = K \frac{S \cos \theta}{d^2} \tag{1}$$

where K is the gain factor and other constants of the system,

S is the photocathode area,

θ is the angle that incident light makes with normal to photocathode surface, and

d is the distance from the source.

Assuming that the energy is transmitted from a surface point-source equally in all directions and that there is no absorption in air, at altitude h

$$d = \frac{h}{\cos\theta} \tag{2}$$

for any value of θ from 0 to 90 degrees.

Substituting Eq. (2) in Eq. (1)

$$E = K\,\frac{S\cos^3\theta}{h^2}. \tag{3}$$

Equation (3) shows how a simple receiver may be expected to be energized when flown through the vertical line above a transmitter under certain idealized conditions. For clear atmosphere a height of several miles can be expected for values of θ near zero since vertical attenuation in the air is due mainly to the inverse square law. But for a given height it is clearly shown by Eq. (3) how the signal strength drops off as θ is increased. In general, it may be said that the cosine, being cubed, is the dominating factor in the equation.

At first glance it would seem that increasing the effective photocathode surface S by optical means would be a simple way of increasing the triggering energy, but in actual field conditions there are many noises, such as that due to background illumination, which an optical system would also collect if the angle of pickup extended over indefinite regions. In other words, the signal-to-noise ratio cannot be improved unless more directivity is introduced into the system.

Two methods thus far have been tried in attempts to increase the signal-to-noise ratio, especially in the peripheral regions of the light cone. In the first method, an optical device similar to a Schmidt system was designed to collect light over an unusually wide angle (Fig. 8). With marked attenuation outside an external optical angle of nearly 90 degrees and almost 100 percent attenuation on the vertical axis, most of the light collected was that arriving at angles from approximately 10 to 45 degrees from the vertical. This was made possible by an unusual design of the secondary mirror which was placed in a coaxial position with respect to the main mirror (diameter, 6 in.; focal length, 4 in.) and the multiplier tube. Due to the loss of skew rays the optical gain in the optimum direction was only of the order of one which is not sufficient for the narrow light cones and high altitudes used in the present experiments. However, under other conditions, such a system could be used to increase the signal-to-noise ratio by several times.

For preliminary experimental flights to collect data at several heights the system shown in Figs. 3 and 4 was used. Rays from forward and backward directions are collected by two multiplier tubes enclosed in a housing with two windows. The light is received in this system in such a way that the optical sensitivity is always in a downward forward and downward backward direction. Thus an arbitrary sensitivity pattern is introduced which serves very well as long as the aircraft flies through the vertical axis of the transmitted light cone. (See Fig. 9.)

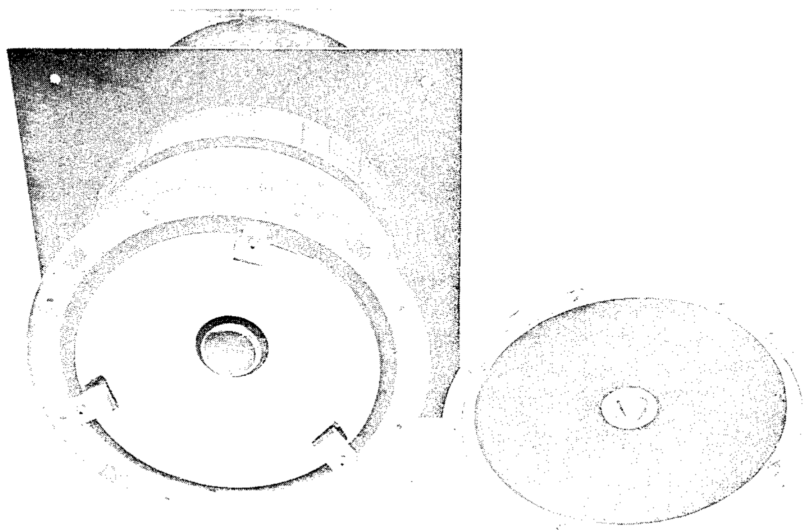

Fig. 8 - Optical parts of single tube pickup unit with parabolic collector, filter, and secondary mirror

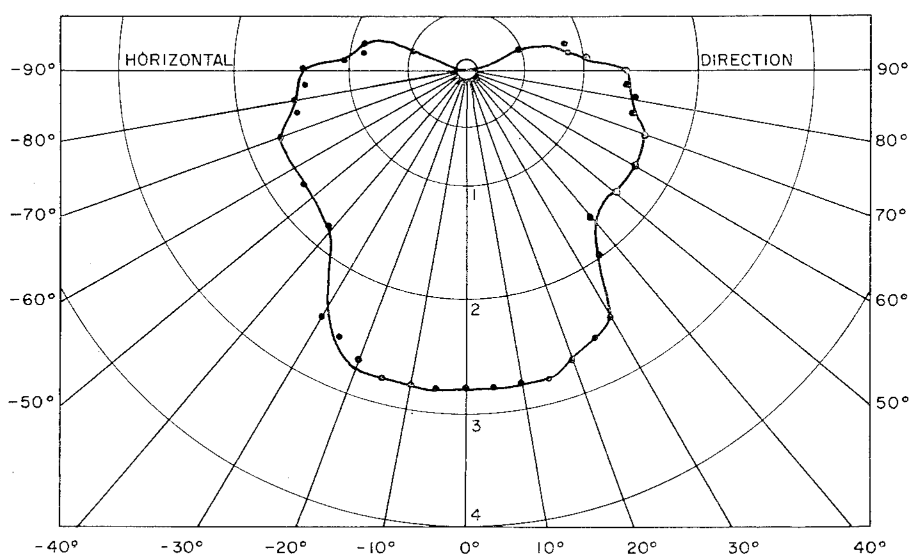

Fig. 9 - Sensitivity pattern of two enclosed 5819 photomultiplier tubes placed 90 degrees apart, scale indicates relative sensitivity in vertical plane through axis of two tubes

[redacted]

When a lens pickup system is installed using Lucite lenses (diameter, 4 in.; focal length, 6 in.) the receiver can receive light in two 40-degree solid angles forward and backward, respectively. This second dual tube unit (Fig. 10), which uses two 6199 multiplier tubes mounted 60 degrees apart and is housed to accommodate the two lenses, has a sensitivity pattern as shown in the polar graph of Fig. 11. The optical gain at an angle of approximately 35 degrees forward and 35 degrees backward is about 3.5.

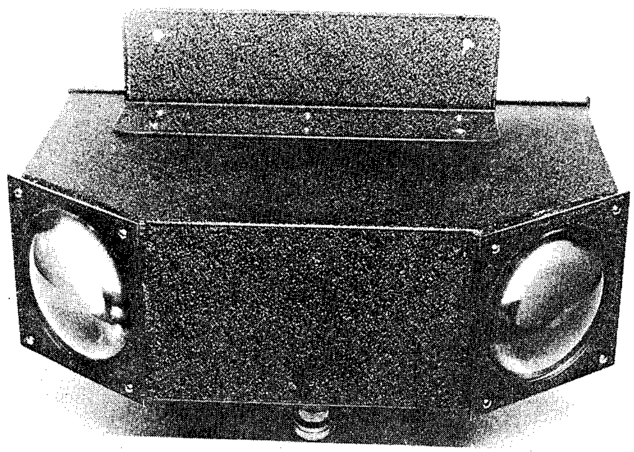

Fig. 10 - Pickup unit using two Lucite lenses; filter holders are built in behind the lenses

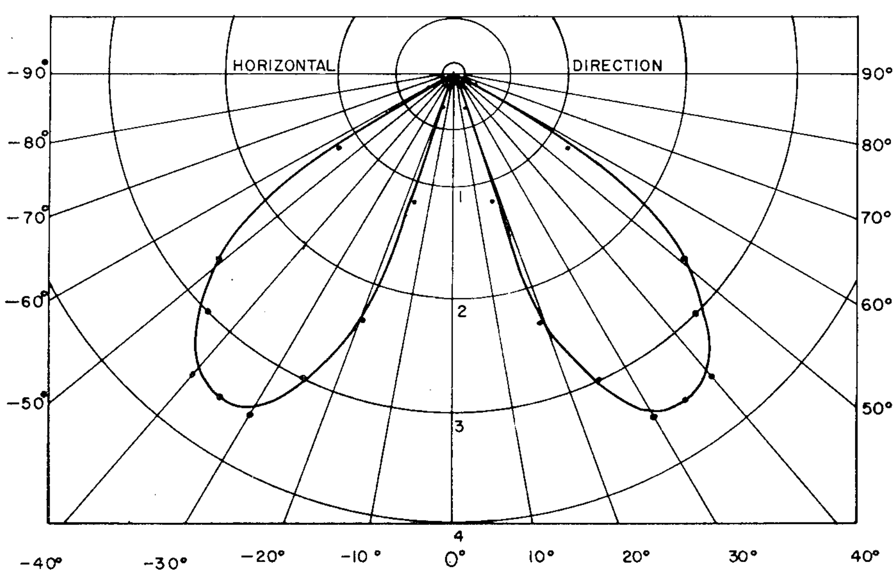

Fig. 11 - Relative sensitivity of dual receiver unit with two Lucite collector lenses before the 6199 photomultiplier tubes

SENSITIVITY OF THE RECEIVER

To simplify the discussion on the sensitivity of the instrument it is perhaps best to consider a receiver utilizing only a single photomultiplier tube (Type 5819 or 6199) and no optical system. For convenience a 5819 multiplier operating into a cathode follower will be considered. The 10-kilohm anode load resistor has the same value as the corresponding resistor in Fig. 5, and the gain ratio of the cathode follower stage is assumed to be unity. This is merely saying that the peak output voltage from the pickup unit (see Fig. 5) is approximately equal to the peak voltage developed across the anode load resistor of the multiplier tube.

After amplification by the 5654 tubes in Unit B (Fig. 6), a peak voltage of 0.2 volt is needed on the grid of the phase-splitter tube (the first 6AC7 of Unit B) to give positive triggering of the circuit. This means that the input voltage to Unit B must have a peak value of at least 0.2 volt divided by the amplification factor of the combined amplifier stages. In all flights to date only two stages on the amplifier strip have been used, with a measured amplification factor of 460 at 50 kc. This makes it necessary to develop a pulse of $0.2/460$ or 4.3×10^{-4} volt at the output of the pickup unit.

With a gain of unity in the cathode follower, the voltage across the 10-kilohm load resistor must then be approximately 4.3×10^{-4} volt and the peak current in the resistor is

$$I_p = \frac{4.3 \times 10^{-4}}{10 \times 10^{3}} = 4.3 \times 10^{-8} \text{ ampere.}$$

The equivalent light input of the tube is computed from the average characteristics given in the RCA Tube Handbook. For the 5819 tube operating with a dynode voltage of 750 volts, 1 ampere has an equivalent light input of 0.25 lumen, and 4.3×10^{-8} ampere provides a light input of approximately 10^{-8} lumen or 10^{-2} microlumen. This is the peak illumination needed on the 2.2-in.^{2} photocathode surface to trigger the receiver.

From the photocathode area and the minimum peak light input needed for triggering, a sensitivity figure of 0.005 microlumen/in.^{2} is obtained. This is more useful than a signal-to-noise ratio since the tube is assumed to be in the dark and the adjustments are made so that practically no triggering takes place without a signal.

When the dynode voltage is very low or zero no dark-current effects in the anode load resistor are noticeable. Adjustments are made on the multivibrator and trigger gain tube under these conditions so that the noise from the amplifier triggers the circuit very infrequently. As the dynode voltage is turned up (to around 750 volts), the dark-current noise begins to exhibit triggering effects due to the fact that peak currents in the load resistor equal or exceed 4.3×10^{-8} ampere. For this reason the final adjustment should be made so that the multiplier tube noise triggers the receiver only at long intervals of time.

It may be of interest at this point to give a brief discussion of what ranges may be expected for a receiver operating under idealized field conditions, i.e., in a vacuum, with total darkness, and operating with a typical flashlamp transmitter.

Peak intensities of the order of 40×10^{6} lumens are produced by the flashlamps used in these experiments, and for simplification no collimating or reflecting devices will be considered. Then, at a distance of 1 foot, the flux density is approximately $(40 \times 10^{6})/1728$ or 2.3×10^{4} lumens/in.^{2}.

[redacted]

Then the distance D_X required to reduce the flux density to 0.005 microlumen/in.^{2}, the threshold value of the receiver, is obtained by the inverse square relation

$$\frac{D_X^2}{1^2} = \frac{2.3 \times 10^4}{0.005 \times 10^{-6}}$$

$$D_X = 2 \times 10^6 \text{ feet} \cong 400 \text{ miles.}$$

If the flashlamp were used in a collimating reflector, the computed distance, assuming ideal conditions, would be much greater than 400 miles, but in any case only idealized conditions would result in such detection ranges. In actual practice, the atmospheric attenuation and background illumination would be major factors in limiting the range.

OPERATION OF THE RECEIVER IN FLIGHT

Once installed the complete receiver is easily adjusted for flight conditions and only needs an occasional readjustment by a small knob or two when the aircraft is flying over land or water.

By referring to the schematic diagram in Fig. 6 the panel controls may be identified in their appropriate circuit positions. These may be listed in the following order:

trigger amplifier,

multivibrator control,

audio gain,

dynode voltage control.

At the beginning of preliminary adjustments, especially with any light entering the pickup unit, the dynode voltage control should be turned back to zero and the trigger amplifier control turned fully counterclockwise. After a short warmup period (15 minutes), the multivibrator can be adjusted to operate near the critical point. This point may be identified with a setting of the multivibrator control which produces only an occasional note in the headphones. For more stable operation, the bias is made slightly more negative on the first multivibrator tube by turning the control knob slightly to the left.

With the multivibrator in proper adjustment the next step is a gain adjustment of the trigger amplifier stage. This control should be turned up until the noise in the amplifier tube begins to trigger the multivibrator and then turned back until the triggering effect is stopped. After warmup and the subsequent adjustment of the multivibrator and amplifier controls, it is only necessary to set the dynode voltage and audio gain controls to suit any existing condition.

In case of total darkness at the multiplier photocathode, the dynode voltage may be turned up (Fig. 6) until the dark-current fluctuations of the multiplier tube produce triggering in the circuit. This usually occurs when the total dynode voltage is approximately 800 volts. Such a high value, it must be emphasized, is seldom used and the voltage must always be reduced to avoid erratic triggering which may be caused by stray illumination of the pickup unit. In the present experimental work no special circuitry is used to control the dynode voltage automatically, and manual control is necessary while the instrument is in use. In flight, however, this voltage control may be set for any ambient lighting condition.

No instructions for operation of the receiver equipment are needed other than those outlined above except to mention that the audio gain may be set to any position which will allow the operator to hear the audio note distinctly. The sound level in the headphones may be raised or lowered depending upon the noise level in the surrounding areas. The instrument is not difficult to operate in flight. Care is necessary to keep the dynode voltage turned back to a proper level, but little attention is required for the remaining controls.

PRESENT STATUS OF THE RECEIVER IN THE EXPERIMENTAL PROBLEM

Only a few brief remarks are necessary in concluding this report: First, the instrument has been used successfully in several flights in a P2V-7 aircraft; secondly, the receiver is being used to obtain range data on a one-way signalling system where the transmitter unit is submerged; and finally, the basic circuits in the instrument are entirely satisfactory for the experimental work being carried on at the present time.

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