AD-A073 483 NAVAL OCEAN SYSTEMS CENTER SAN DIEGO CA F/G 17/2

RAPCAP: AN OPTICAL COMMUNICATIONS HELMET.(U)

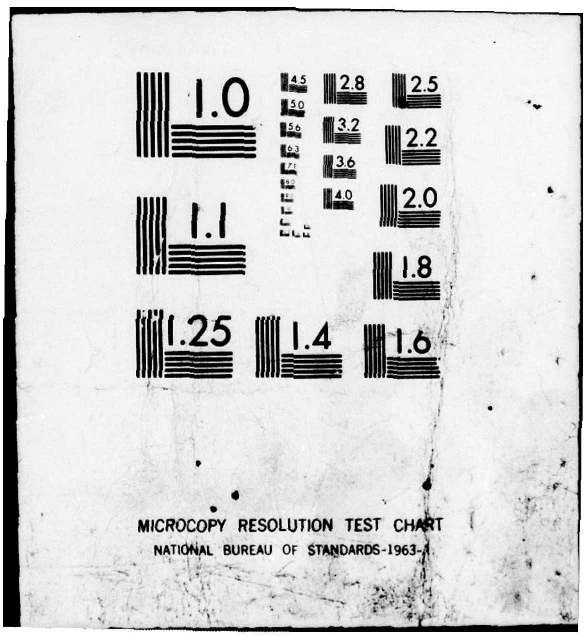
JUN 79 G M MEANA, R H PATTERSON, J M MARABEAS

UNCLASSIFIED NOSC/TR-401 NL

1 OF 1

AD
A073483

END
DATE
FILMED
10-79
DDC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

LEVEL VI 12

NOSC

NOSC TR 401

NOSC TR 401

Technical Report 401

RAPCAP: AN OPTICAL COMMUNICATIONS HELMET

GM Meana
RH Patterson
JM Marabeas
DR GC Mooradian

1 June 1979

Prepared for
Naval Sea Systems Command
(Code 512)

Approved for public release; distribution unlimited

NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CALIFORNIA 92152

NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CA 92152

AN ACTIVITY OF THE NAVAL MATERIAL COMMAND

RR GAVAZZI, CAPT USN
Commander

HL BLOOD
Technical Director

ADMINISTRATIVE INFORMATION

The development effort described in this report was performed by members of the Communications Research and Technology Division, EO and Millimeter Wave Communications Branch, under Program Element 6305N, Project S0398-SL, Task Area 15625, and Work Unit CM34. The work was sponsored by the Naval Sea Systems Command (NSEA-512). Mr. K.C. Morisseau was Washington project manager.

Released by
Marlan S. Kvigne, Head
Communications Research and
Technology Division

Under authority of
H.D. Smith, Head
Communications Systems and
Technology Department

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER NOSC Technical Report 401 (TR 401)	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

(6) RAPCAP: AN OPTICAL COMMUNICATIONS HELMET.

5. TYPE OF REPORT & PERIOD COVERED

Development 1977-78

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

(10) G.M. Meana, J.M. Marabeas, R.H. Patterson, G.C. Mooradian

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Naval Ocean Systems Center
San Diego, CA 92152

(12) 28 p.

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

6305N, S0398-SL, 15625, CM 34

11. CONTROLLING OFFICE NAME AND ADDRESS

Naval Sea Systems Command
(NSEA-512), Washington, DC

393 159

12. REPORT DATE

(11) 1 June 1979

13. NUMBER OF PAGES

38

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

(14) NOSC/TR-401

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(9) Technical rept.

18. SUPPLEMENTARY NOTES

(16) S0398 (17) S0398SL

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Optical communications
Underway replenishment
Low probability of intercept
EMCON

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The RAPCAP underway replenishment communications system is designed to provide rig team-to-rig team voice communication between ships during underway replenishment (UNREP). The system employs a helmet-mounted optical transceiver that operates in the near infrared. Good-quality voice communications have been achieved beyond typical UNREP intership ranges of 75 metres. Because of its short range, RAPCAP is covert and can be used during emission control (EMCON) conditions. The system will reduce manpower requirements, enhance safety, and reduce time on station during the close-in coordinated maneuvers associated with at-sea replenishment operations.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

393 159

PROBLEM

Develop and demonstrate a low-probability-of-intercept optical technique for achieving short-range intership voice communications between underway replenishment (UNREP) rig teams during EMCON conditions.

RESULTS

A brassboard helmet-mounted optical transceiver was developed and tested. Good-quality voice communications were achieved beyond typical UNREP intership ranges (75 metres).

RECOMMENDATIONS

An operational ultrashort-range covert communication system based on electro-optical principles should be developed. The system should be designed to achieve the following:

- Intercept-resistant voice communications for use during EMCON ALPHA.
- Reduced manpower requirements at liquid/dry cargo transfer stations during connected replenishment (CONREP).
- Enhanced safety during close-in coordinated maneuvers.
- Reduced time on station during replenishment.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (continued)

TABLES

EXECUTIVE SUMMARY

The Naval Ocean Systems Center proposed a systems concept in 1977 to NAVSEA's Amphibious/Auxiliary Ship Logistic Division for underway replenishment (UNREP) rig team-to-rig team low-probability-of-intercept (LPI) voice communications. Subsequently, a NOSC development team from the Communications Research and Technology and the Command Support Divisions produced a brassboard system under NAVSEA sponsorship. This underway replenishment communications (RAPCAP) system is a helmet-mounted optical transceiver. The unit is intended to demonstrate the feasibility of an electro-optical technique for rig captain-to-rig captain communications during emission control (EMCON) conditions.

The brassboard hardware has undergone NOSC evaluation tests. Good-quality voice communications have been achieved beyond typical UNREP intership ranges (75 metres). The units have performed successfully under restricted solar background conditions during battery-pack operation. A performance evaluation of the RAPCAP brassboard system was successfully conducted during UNREP operation in late June 1978.

An ultrashort-range covert communication system based on advanced electro-optical principles is technically and economically feasible. Development/procurement of this lightweight man-worn equipment will

- Provide an intercept-resistant voice communication link for use during EMCON ALPHA.
- Reduce manpower requirements at liquid/dry cargo transfer stations during connected replenishment (CONREP).
- Enhance safety during close-in coordinated maneuvers [eg, CONREP and vertical replenishment (VERTREP)].
- Reduce time on station during replenishment.

1.0 INTRODUCTION

This report addresses a critical Fleet need for short-range, intercept-resistant communications and presents an electro-optical solution which promises to be low in cost and reliable, and to reduce manpower levels.

During FY 77, NAVSEA's Amphibious/Auxiliary Ship Logistic Division (Code 941) requested that the Naval Ocean Systems Center, San Diego, propose an advanced system concept (ASC) for a helmet-mounted optical transceiver for UNREP station-to-station communications. This system was to be capable of operation even under the strictest emission control (EMCON) conditions. Subsequently, NOSC was funded by NAVSEA 941 to demonstrate the feasibility of the concept during FY 78. This effort resulted in brassboard hardware for the RAPCAP system. The near-infrared optical frequency was selected to conform to a water-vapor absorption band in the atmosphere. Thus the system derives its covertness from limited signal range. The helmet-mounted configuration is expected to satisfy a variety of ultrashort-range (less than 100 metres) communications requirements.

In any confrontation with the Soviets, many elements of the US Fleet would spend extended periods at sea, and forward-area underway replenishment (UNREP) would take the place of most in-port resupply. Time on station or alongside during UNREP would become critical.

Modern naval tactics demand management of all electromagnetic and acoustic emissions (eg, EMCON conditions ALPHA or SIERRA). Concealing the existence, location, and composition of friendly naval forces can be of the highest tactical value. Naval task forces are increasingly subject to sophisticated surveillance by Soviet COMINT ships, shore direction-finding stations, and airborne platforms. The interception of fragmented, relatively insignificant communications can be skillfully used to ascertain important tactical information.

Effective intership communication plays a major role in accomplishing UNREP's essential mission. The ability to conduct real-time, wire-free voice communications has been shown to contribute significantly to safety, effectiveness, and reduction of manpower in the UNREP mission[1]. There is great interest in providing this same capability under EMCON conditions.

A particularly urgent voice communication requirement exists for mobile logistic support scenarios. Present interplatform communications methods are outmoded and plague both the customer ship and the replenishment platform. There are hard-wired ship-to-ship links between liquid/dry cargo transfer stations during CONREP. The sound-powered phone (SPP) lines supporting these transfer stations require several minutes of setup time after two ships are alongside. Often the wired links part or jack boxes short out. Signalmen are available for backup, but this method is exceedingly limited for normal operations and unsatisfactory for emergency breakaway.

The seriousness of the SPP problem was aptly expressed by a CARDIV commander as follows: "The present sound-powered phone circuits with their unreliable equipment and untrained talkers and the absence of an effective means of wire-free communications (WFC) with 'men-on-the-move' probably do more to reduce the combat capabilities of

---

[1] Naval Electronics Laboratory Center, Manpower Reduction via Improved Intership Communications During Connected Replenishment at Sea, by FG Henry and EW Davenport, NELC TR 1936, 1 November 1974.

our ships than any other single item." Recent studies[2] aboard deployed support vessels demonstrated a means of significantly improving intership communications. The study established that (1) it is operationally feasible and safe for rig captains to utilize WFC between ships during CONREP as a substitute for station-to-station talkers and signalmen; and (2) the additional task of communication does not interfere with the rig captain's primary job. The objective of the NOSC RAPCAP program was to demonstrate an electro-optical method to address this rig captain-to-rig captain communications requirement.

2.0 HUMAN FACTORS CONSIDERATIONS

The main purpose of the program was to demonstrate an optical technique for intership voice communications between underway replenishment (UNREP) rig teams during EMCON conditions. An important part of this objective was to gain user acceptance of such equipment. The preliminary system configuration should satisfy many human factors criteria to assure a high initial degree of user acceptance.

Therefore, NOSC Command Support Division personnel submitted the following information pertaining to human factors and user need aspects of an optical transceiver for an UNREP rig team captain.

GENERAL DESIGN PHILOSOPHY

There are many engineering reasons for the design and packaging of the optical transceiver as a single, integrated, head-worn package – the foremost being the elimination of external cords and plugs. Other reasons are ease of shielding and ease of storage and handling. From the wearer's point of view, the single-package helmet is the ideal configuration. An integral helmet design not only facilitates donning and doffing, but is generally safer since there is no interconnecting cable to become snagged. Certainly, the design goal for any **production** model of such a system should be a single, integrated, lightweight, head-mounted package. However, the brassboard models for exploratory development efforts need not adhere strictly to that single-package concept. It is recognized that the main technical/operational objectives can be achieved if, for example, the battery (power pack) is separated from the head-mounted gear.

As pointed out in TR 1936, rig captains are **constantly on the move**, with their attention focused mainly on deck activity in the immediate vicinity of their own transfer rig. The system must not interfere with the rig captain's need to move about freely within his transfer station. Most important, any **production** WFC system must be such that the rig captain does not have to preposition himself for receiving. The equipment should therefore be designed to have an omnidirectional receive capability. The transmitter's field of view (FOV) of 180° in azimuth and ± 30° in elevation from the rig captain's line of sight should suffice for demonstration/test purposes of the brassboard equipment.

POWER SUPPLY LOCATION

In the interest of simplifying the head-mounted equipment package and reducing the overall weight of components on the head, the following was suggested for the **breadboard** models:

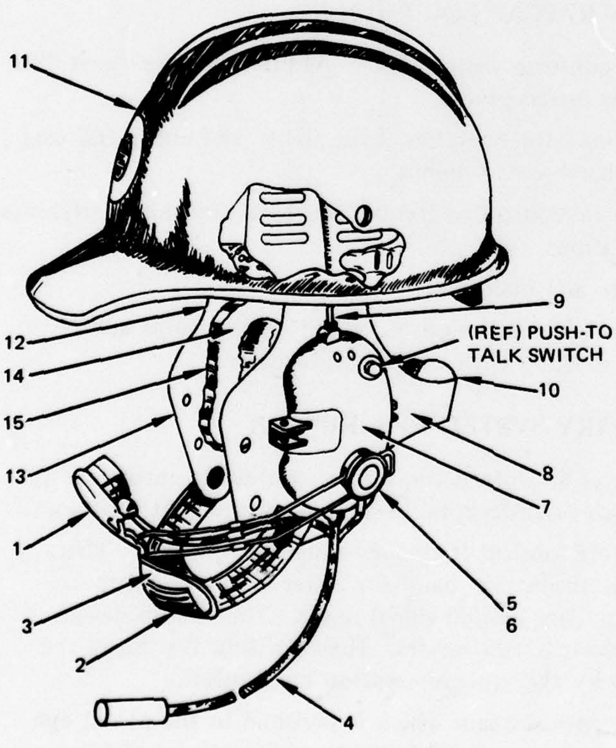
---

[2] Naval Ocean Systems Center, At-Sea Demonstration of RAPCAP, by EW Davenport, NOSC TN 573, 1 November 1978.

1. Separate the battery unit/package from the transceiver.
2. Design the battery package for body mounting. The best location is from the belt. (Other locations for battery mounting on the body have been tried, including lapel-pocket mounting, but the advantages of shorter cables to the transceiver are generally outweighed by problems of fit and securing the battery in the pocket.)
3. To facilitate battery charging and/or changing during the operational at-sea test phase, the battery pack should be easily removable from the belt-supported holster. A quick-disconnect plug also should be incorporated to ensure that the headset can remain on the user's head while a rapid battery substitution is made.

SAFETY CAP HEADSET

Figure 2.1 is an engineering drawing of the safety cap headset, CD–H357R, assembled by Carter Engineering Company, Inglewood, CA. The hardhat itself is manufactured by the Bullard Company of Sausalito, CA. It meets or exceeds the safety standards required by the Navy during CONREP. Carter Engineering has incorporated their own headset and several special features for making the package comfortable and secure on the user's head. Headset transducers comprise the M87 microphone and the earphone unit H–143/AIC. The CE–H357R contains an inside liner for suspending the hardhat approximately 2 inches from the user's head.



MIC BOOM ASSY	1
CHIN STRAP	2
CHIN CUP	3
HARNESS ASSY	4
WASHER, NYLON	5
THUMB SCREW	6
EAR CUP LH	7
SUPPORT, EAR CUP LH	8
HARNESS ASSY	9
PAD, NECK	10
CAP SAFETY	11
EAR CUP RH	12
SUPPORT, EAR CUP RH	13
EAR SEALS	14
SANITATION COVER, NYLON	15

Figure 2.1. Safety cap headset.

HEADSET

It is essential that only one side of the rig captain's head be equipped with an earphone. The other ear must be uncovered to hear direct speech, warning signals, etc. Accordingly, the safety hat/headset package will utilize two ear cups, only one of which will be equipped with an earphone; the other ear cup will be open. This arrangement should provide an adequate seal around the user's ear such that ambient noise is excluded from the earphone-equipped cup.

PUSH-TO-TALK SWITCH

A push-to-talk switch (PTS) located in the headset is preferred over other PTS options–including either that of a hand-held switch or one located in the battery pack. Both the latter PTS options have been tried in at-sea test configurations and have been rejected by users–especially by rig captains who are physically active The hand-held PTS requires an interconnecting cable which users do not like; the battery-pack PTS is often difficult to reach, especially when foul weather gear is worn. Note also that voice-actuated (VOX) transmission is operationally undesirable. TR 1936 points out that the rig captain does a lot more talking directly to the personnel around him than to his counterpart on the opposite ship. A push-to-talk system would not be actuated during direct conversation.

The above considerations naturally give rise to general design characteristics for production of the RAPCAP equipment.

REQUIREMENTS OF PRODUCTION RAPCAP EQUIPMENT

- Must be intercept-resistant to conform with EMCON ALPHA and the Quiet Task Force concept. **Rf radiation is unacceptable.**
- Must be human-factors engineered for operational simplicity and enjoy full user acceptance in an exceedingly harsh environment.
- Must operate on up to 10 crystal-controlled frequencies to assure noninterference between adjacent CONREP stations.
- Must be economical to procure and maintain.
- Must be compatible with all new-construction Navy and civilian ships and be capable of easy retrofit to all existing USN ships worldwide.

3.0 PRELIMINARY SYSTEM DESCRIPTION

The RAPCAP helmet consists of an optical transceiver configured into a safety hardhat. The design features emphasize user acceptance as well as intercept resistance.

RAPCAP operates in the near–IR optical frequency range of 0.93 μm. This design frequency conforms to a broad absorption band for water in the atmosphere. Thus the system derives its covertness from limited signal range. The system design range for intership voice communications is 100 metres. Hence within this range the solar background flux is also reduced by the same absorption mechanism.

RAPCAP transmits a near–IR optical beam which is invisible to the naked eye. This beam is formed from three Texas Instruments GaAs light-emitting diodes (LEDs).

Each can emit an average optical power of 350 mW. Reflecting optics are designed to form a transmitter pattern of 180 degrees in azimuth and ± 30 degrees in elevation. The optical receiver envelope is 360 degrees in azimuth and ± 45 degrees in elevation. Such a wide-field-of-view optical design allows maximum user mobility. The optical receiver consists of five circular silicon detector modules arranged around the perimeter of the helmet. Each detector module contains a colored glass spectral filter (RG 850), an 8-cm^2 photodiode, and a tuned preamplifier. The RAPCAP system uses incoherent optical transmitters and direct-detection receivers. The system is free from the multipath effects which affect other communications techniques when applied to a short-range and wide-field-of-view requirement.

At present, the RAPCAP optical transmitter is driven by a single sideband (ssb) modulator. Ssb is an arbitrary choice based on the availability and cost of electronic components. (Further work in this area will utilize an fm format because it affords numerous discrete channels.) Each helmet has the push-to-talk switch located on the ear cup. The microphone is a Military Standard M87 noise-canceling unit with an average sensitivity of 3 μV at 74 dB sound pressure level. The voice is processed via normal ssb circuits and converted to an if of 82.6 kHz. This if "carrier" is used to current-modulate the GaAs LED transmitter array. A Plexiglas shield protects theLEDs from the ambient environment.

The electronic receiver sums the ssb signal received from each of the five optical detector modules into an 85-kHz receiver with agc. The demodulated signal is fed to an externally controlled audio amplifier/earphone set. The entire ssb transceiver is contained on a printed circuit board positioned in the crown of the helmet. The linear LED power driver is "piggy-backed" on top of the transceiver board.

Each helmet unit is powered by a belt-mounted rechargeable battery pack. The helmet and battery pack each weigh about 3 pounds. The battery pack uses light NiCd D-cell batteries and will supply power for 2 hours of continuous operation. A "quick-pak" battery was also designed. It weighed a little less than 1 pound and used four nonrechargeable lithium batteries. This unit was very useful for demonstrations and tests lasting about 30 minutes.

4.0 SYSTEM DESIGN ANALYSIS

The RAPCAP system is required to provide LPI voice communication out to a maximum range of 100 metres in full daylight. The system must employ a minimum-weight transmitter and receiver and require virtually no pointing (ie, the sender merely faces the general direction of the receiver, which has no prepositioning requirements). This general scenario translates into the following baseline system parameters.

1. Transmitter parameters:
   - Optical source: three high-power (max 350 mW each) IREDs
   - Transmitter spectral band: 9300–9500 Å
   - Reflector optics field of view: 180° azimuth, ± 30° elevation
   - Electronic carrier frequency: 83 kHz.
2. Detector parameters:
   - Silicon photodiodes active area: 8 cm^2
   - Five detectors spaced around helmet perimeter

- Responsivity at 9300 Å: 0.45 A/W
- Noise equivalent bandwidth: 2.4 kHz.

The RAPCAP optical transmitter uses three high-power GaAs infrared-emitting diodes (IREDs) with maximum 350 mW average optical output at a wavelength centered at 9330 Å and half-power optical bandwidth of 450 Å. The radiant intensity for the transmitter beampattern of 180° azimuth and ± 30° elevation for a single IRED device is 80 mW/sr. The geometry of the reflective optics gives rise to a measured maximum optical gain of three along the normal line of sight for a user. Hence the RAPCAP optical transmitter has a maximum radiant intensity at 3 A average of

$$\left[I_{AVE}\right]_{MAX} = 240 \text{ mW/sr}. \quad (4.1)$$

For the purposes of this analysis, the instantaneous peak radiant intensity is the parameter of interest since the photodiode detector was transformer-coupled to the preamplifier. The transmitter's average current drive was limited to 0.75 A. The transmitted waveform was a half-wave-rectified sine wave at the carrier frequency of 83 kHz. From Fourier analysis, the peak-to-average ratio for a half-wave-rectified sine wave is π. Since

$$I_{AVE} \text{ at } 0.75 \text{ A} = 25\% \left[I_{AVE}\right]_{MAX} = 60 \text{ mW/sr}, \quad (4.2)$$

then the peak radiant intensity at an average current of 0.75 A is given by

$$I_{PEAK} = \pi \, I_{AVE} = 188 \text{ mW/sr}. \quad (4.3)$$

The transmittance of the typical maritime atmosphere for a 1000-ft path at sealevel is 60% at a wavelength of 9300 Å. Therefore, the absorption coefficient is -7.3 dB/km. Hence the effective radiant intensity at four operationally significant ranges is given in table 4.1.

Table 4.1. Effective radiant intensity at four operationally significant ranges.

Range, m	I_{EFF}, mW/sr
100	160
75	166
50	173
25	181

The peak energy density incident on the receiver's entrance aperture is given by the product of the peak radiant intensity at the detector and the solid angle Ω subtended by the receiver's entrance aperture (A).

$$\Omega \text{ receiver} = \int \frac{dA \text{ receiver}}{R^2} = 2\pi \int_{\theta=0}^{\theta_{rec}} \sin\theta \, d\theta. \quad (4.4)$$

Results of evaluation of the above integral for the geometry depicted in figure 4.1 are presented in table 4.2 for an 8-cm^2 entrance aperture.

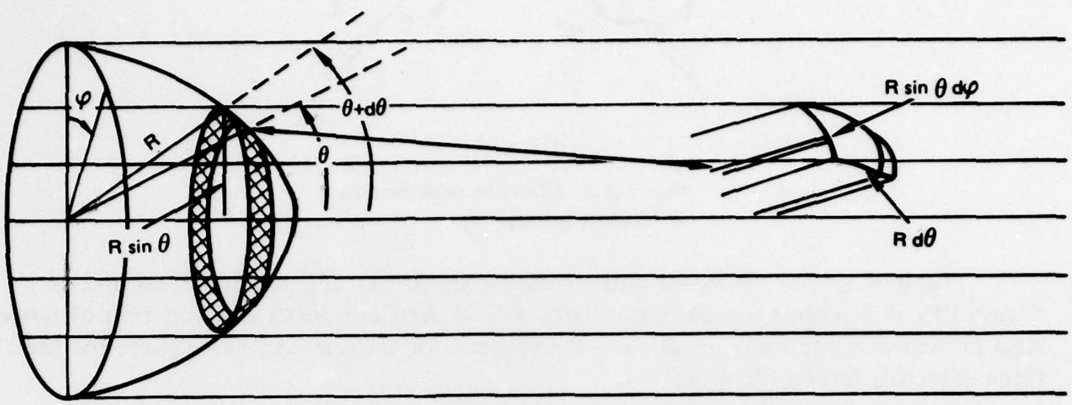


Figure 4.1. Geometry for evaluating the solid angle subtended by receiver A.

Table 4.2. Receiver solid angle at range R.

Range, m	Ω Solid Angle, sr
100	8×10^{-8}
75	14×10^{-8}
50	32×10^{-8}
25	128×10^{-8}

The peak optical power incident on a receiver's detector at range R is the product I_{EFF} times Ω receiver.

Table 4.3. Peak received power per detector.

Range, m	Φ, W
100	12.8×10^{-9}
75	23.2×10^{-9}
50	55.4×10^{-9}
25	231.7×10^{-9}

Figure 4.2 depicts the geometrical orientation of the detectors pointed into the user's forward hemisphere. For the three forward-looking detectors, each having 8 cm^2 of active area, the total effective detector cross section is

$$A_{EFF} = A\,(1 + 2 \cos 55°) = 2.14\ A = 17.12\ cm^2. \qquad (4.5)$$

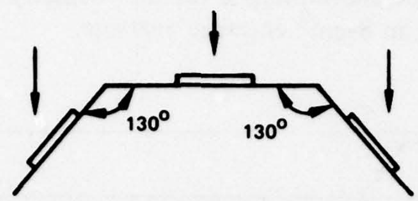


Figure 4.2. Effective receiver area in forward hemisphere.

Table 4.4 gives the signal current with a single RG 850 spectral filter and an 8-cm^2 PIN photodiode whose responsivity is 0.45 A/W at 9300Å as a function of range. Also tabulated is the total signal current expected for the forward hemisphere for the three detectors in combination.

Table 4.4. Received signal current.

Range, m	I_{SIG}, nA	Total I_{SIG}, nA
100	5.8	12.4
75	10.4	22.3
50	25.0	53.5
25	104.3	223.2

A typical parameter for the predicted performance of an electro-optical system is the average signal-to-noise power ratio.

$$SNR = \frac{I^2_{SIGNAL}\ r_{LOAD}}{N_{TOTAL}}$$

where $N_{TOTAL} = G_i\ r_{LOAD}\ f$

$$G_i = 2\ q\ I_p$$

$$I_p^2 = I^2_{BACKGROUND} + I^2_{DARK} + I^2_{SIGNAL} + I^2_{THERMAL}.$$

The noise power spectral density (G_i) is given in current units, as is the rms photodetector current (I_p). The transformer-coupled preamplifier circuit yields an effective load impedance (r_1) of 190 Ω at the electronic carrier frequency of 83 kHz. The rms thermal noise current per detector is given by

$$I_{THERMAL} = \left[\frac{4kT\Delta f}{r_1}\right]^{1/2} = 0.46 \times 10^{-9}\ A.$$

The dark current (I_D) generated by an 8-cm^2 PIN photodiode is 3 μA. The total signal currents are given in table 4.4.

The system is to be operable over wide viewing angles and ordinary ambient conditions. As such, it will be limited in performance by the noise arising from the sun-generated detector current. The RAPCAP receiver will be exposed to a large flux of sky-scattered (indirect) solar radiance, and could be exposed to both direct and indirect sunlight. For the purposes of this program, daytime performance under **maximum indirect** sunlight was acceptable.

An experimentally measured spectrum of solar irradiance for a sun zenith angle of 48° is presented in figure 4.3. [3]

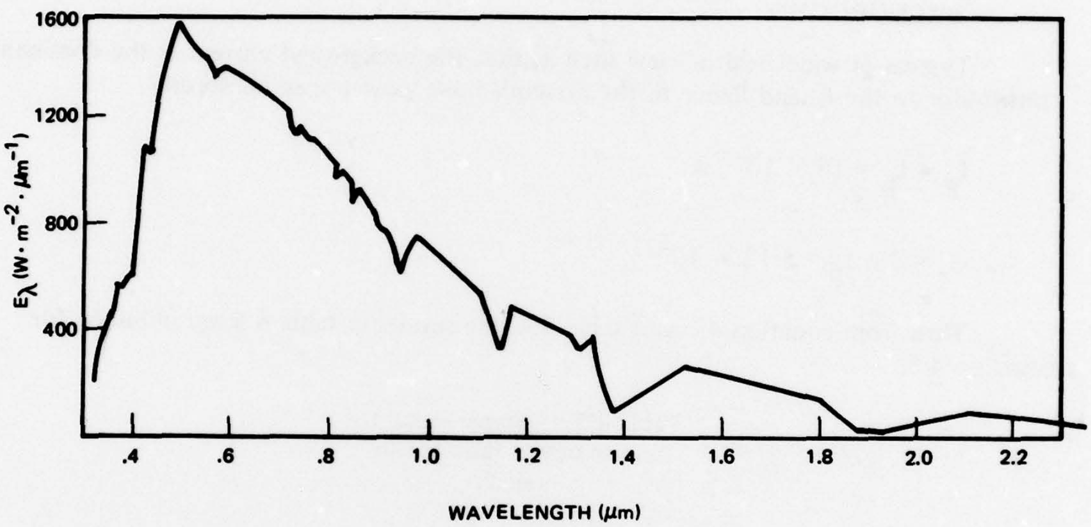


Figure 4.3. Solar spectral irradiance.

The data for the total spectral irradiance from 0.2 μm to 1.2 μm have been integrated. The resultant total irradiance is 94 mW/cm^2. It is imperative that this background flux be spectrally filtered to prevent saturation of post-detection electronics. The present system employs a red-colored glass long-pass filter (Schott glass RG 850). The optical transmission at 9300 Å is 90%. Partial integration of the curve in figure 4.3 over the near-infrared spectrum shows 20% of the direct solar irradiance (19 mW/cm^2) to be contained in this spectral window. If one convolves the solar irradiance distribution in this spectral region (8500 to 12 000 Å) with the spectral responsivity for the PIN detector, then the direct sun-generated background current is about 50 mA. The ratio of the indirect to the direct solar irradiance is typically 10% to 20%. Hence the background current (I_B) per detector is expected to be 5 - 10 mA.

The geometry of the actual operating conditions could allow for more optimistic values. For example, all five detectors point toward the horizon and hence only the upper field of view sees the sky-scattered solar radiance. Furthermore, some of the receivers may be aimed at the sending or receiving ship's structure. However, it is better to be prudent in the present analysis since future programs should deal with operation under direct solar irradiance conditions.

---

[3] Thekaekara, MP, private correspondence.

The system uses five photodetectors for an omnidirectional receive capability. The RMS contribution from each of the five detectors, for $I_{THERMAL}$, I_{DARK}, and $I_{BACKGROUND}$, yield the following total values for the receiver:

$$I_{THERMAL} = 1.0 \times 10^{-9} \text{ A}$$

$$I_{DARK} = 6.7 \times 10^{-6} \text{ A}$$

$$I_{BACKGROUND} = 16 \times 10^{-3} \text{ A.}$$

Typical of wide field of view such as this, the background current is the dominant contributor to the I_P and hence to the system's noise power spectral density.

$$I_P \equiv I_B = 16 \times 10^{-3} \text{ A}$$

$$G_I = 2\,q\,I_P = 5.12 \times 10^{-21}.$$

Thus from equation 4.7 and table 4.4, the results in table 4.5 are obtained for equation 4.6.

Table 4.5. Average signal-to-noise power ratio versus range.

Range, m	SNR, dB
100	+5
75	+10
50	+18
25	+30

For completeness, table 4.6 gives this expected performance prediction for the single detector in the rear of the helmet.

Table 4.6. Average signal-to-noise power ratio versus range for single RAPCAP detector.

Range, m	SNR, dB
100	- 1
75	+ 3
50	+11
25	+24

Figure 4.4 is a graph of the expected performance levels for RAPCAP's forward three-receiver combination. Also depicted is the expected performance for an average

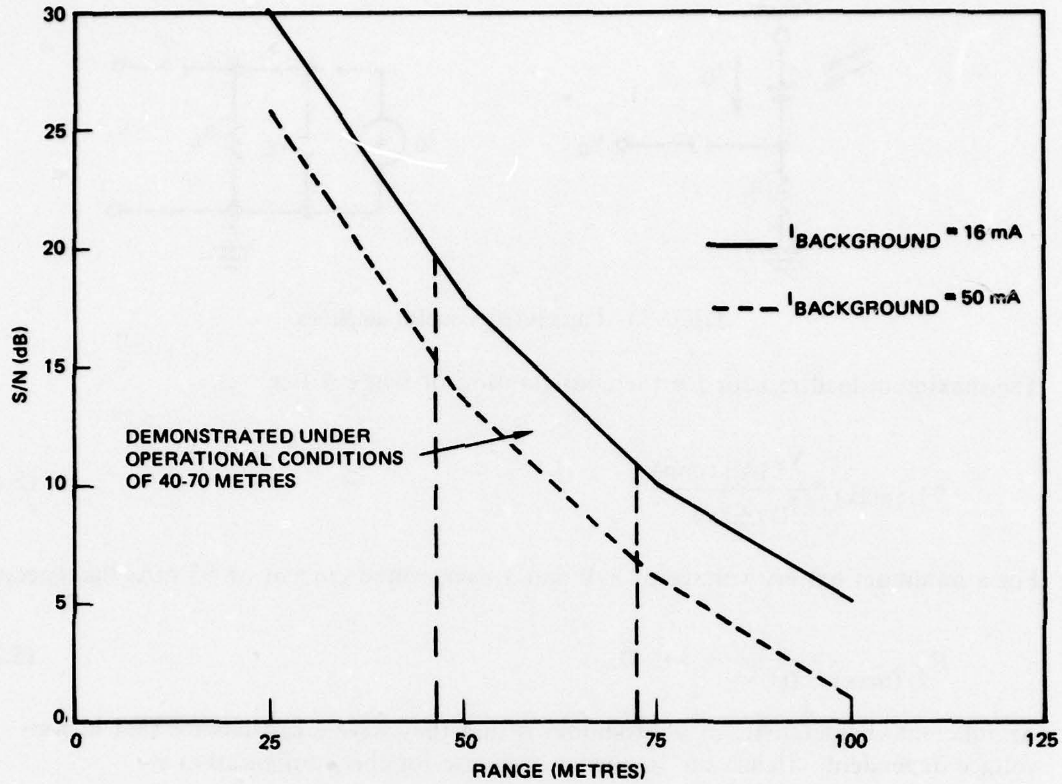


Figure 4.4. Average signal-to-noise power ratio.

SNR if one detector is exposed to direct sunlight (50–mA curve). The normal intership ranges during UNREP are illustrated. The RAPCAP system was demonstrated at these ranges and the performance agreed well with the predictions.

5.0 SYSTEM COMPONENT DESCRIPTION

Single-sideband modulation was chosen for the UNREP system as the best means of conserving battery power while delivering usable intelligibility under low S/N conditions. Of special interest in this system is the unconventional method of coupling between the optical sensor and the preamplifier. The high detector current arising from the solar background precluded the use of capacitively coupled or transimpedance amplifiers without adversely affecting receiver performance. Transformer coupling was chosen to remove detector bias variations while giving greater selectivity and hence higher S/N ratios at the preamp output than other methods.

To demonstrate the advantage of transformer coupling, it is necessary to discuss capacitively coupled and transimpedance amplifiers.

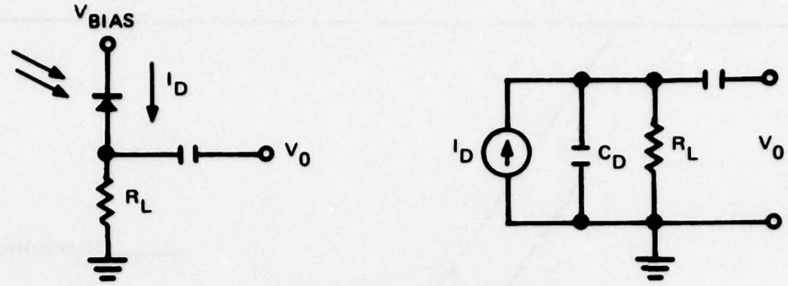


Figure 5.1. Capacitively coupled amplifier.

The maximum load resistor for the configuration of figure 5.1 is

$$R_{L\,(max)} = \frac{V_{BIAS\,(min)}}{I_{D\,(max)}} . \tag{5.1}$$

For a minimum battery voltage of 8 V and a background current of 55 mA, this becomes

$$R_{L\,(max)} = \frac{8}{0.055} = 145\ \Omega. \tag{5.2}$$

An inherent characteristic of photodiodes is that they have a capacitance that is bias-voltage dependent. Hence the frequency response for this configuration is

$$f = \frac{1}{2\pi R_L C_0} \tag{5.3}$$

With no background current, the photodiode capacitance ≈ 1000 pF at 8–V bias and the frequency response is

$$f = \frac{1}{2\pi(145)\,(1 \times 10^{-9})} = 1.1\ \text{MHz}. \tag{5.4}$$

However, with a background current of 55 mA, the voltage across the photodiode is zero and the capacitance is now 6000 pF. The frequency response then becomes

$$f = \frac{1}{2\pi(145)\,(6 \times 10^{-9})} = 18.3\ \text{kHz}. \tag{5.5}$$

This value of load resistor satisfies the dc and signal frequency conditions, but reduces the signal dynamic range. For this reason, a load resistor of 100 Ω would be a more realistic value that would give a reasonable dynamic range to the signal voltage developed across R_L.

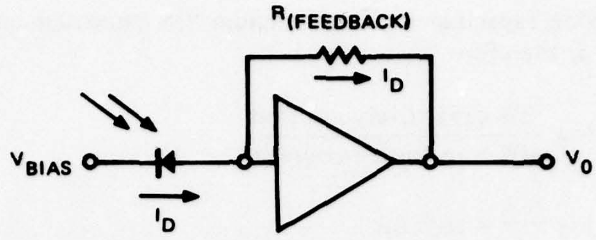


Figure 5.2. Transimpedance amplifier.

The transimpedance amplifier (figure 5.2) converts the photodiode current to a voltage according to

$$V_0 = I_D R_F. \tag{5.6}$$

A single battery supply for this case reduces the photodiode bias voltage because of tradeoffs between amplifier bias and output dynamic range considerations; ie, biasing the amplifier output to half the battery supply voltage reduces the value of load resistor to

$$R_L = \frac{4V}{0.055A} = 72\ \Omega. \tag{5.7}$$

To achieve a useful dynamic range, this value would be further reduced to about 50 Ω. Regardless of these considerations, the amplifier must be capable of supplying the 55 mA of background current to the load resistor for the input terminal to remain at virtual ground and hence maintain a constant bias voltage across the photodiode which is independent of diode current. Needless to say, no amplifier could be found which would meet these criteria.

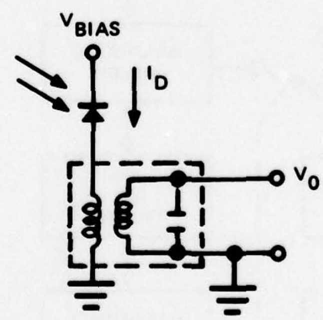


Figure 5.3. Transformer-coupled amplifier.

For a primary winding resistance of 1.3 Ω and a background current of 55 mA, the detector bias in the transformer-coupled amplifier (figure 5.3) will only change by 71.5 mV. Hence there is effectively no loss of detector bias because of voltage drops across the load. At the resonant frequency of the secondary, the effective impedance of the primary is about 200 Ω. Thus the transformer presents a higher load impedance to the sensor than can be achieved with the capacitively coupled or transimpedance approaches. The transformer reduces the bandwidth to 4 kHz, which is independent of the diode junction capacitance. The minimum S/N improvement over a capacitively coupled amplifier is therefore

$$\text{SNI} = 10 \log \frac{\text{BW capacitively coupled}}{\text{BW transformer-coupled}} \tag{5.8}$$

$$= 10 \log \frac{183}{4} = 16.6 \text{ dB.}$$

The dynamic range of the transformer-coupled amplifier is greater than 80 dB, and is independent of background current.

The transformer-coupled preamplifier used in the RAPCAP system has the following characteristics:

1. Equivalent input noise = 0.37 μV
2. Gain = 30 dB
3. Bandwidth = 4 kHz
4. Dynamic range = 80 dB
5. Noise equivalent input (NEI) = 2.9×10^{-11} A/Hz
6. Noise equivalent power (NEP) = 7.3×10^{-11} W/Hz.

The RAPCAP SSB transceiver block diagram (figure 5.4) provided the least complicated approach to this form of modulation, yet enabled the electronics to be mounted in the limited space available.

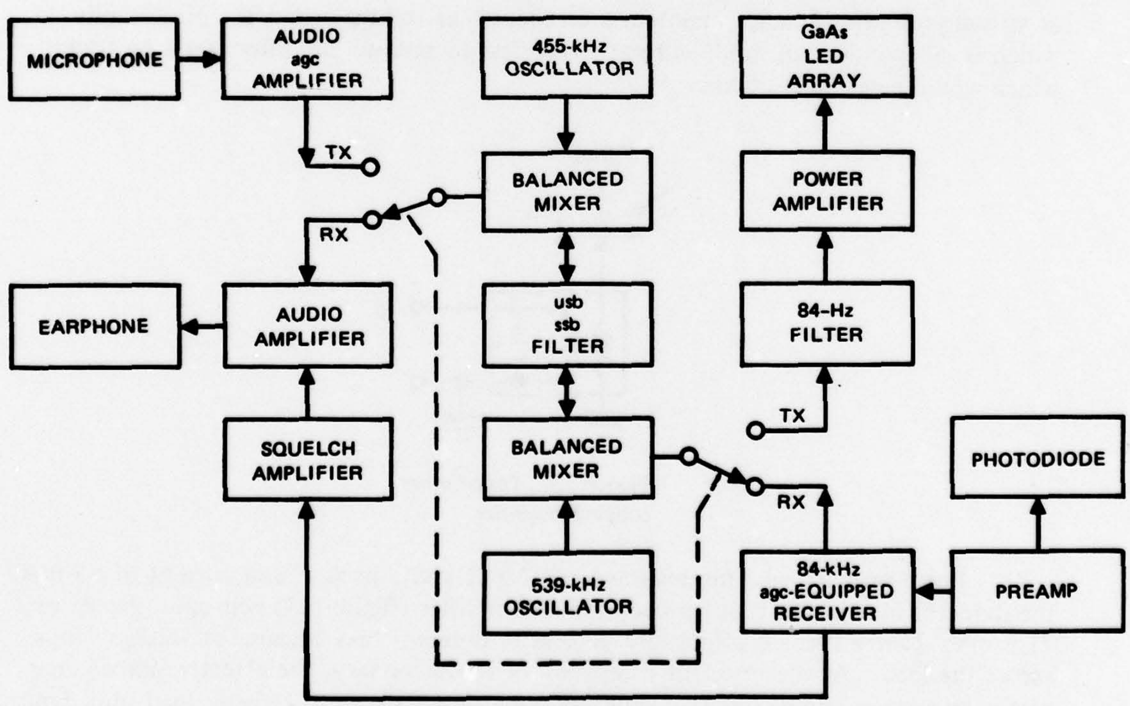


Figure 5.4. RAPCAP helmet electronic block diagram.

In the receive mode of operation, the outputs from the five detector-preamp modules are summed before being applied to a common receiver. The receiver output is mixed with the 539-kHz oscillator to yield products of 455 kHz and 623 kHz. Only the upper sideband (usb) components about 455 kHz are passed by the Collins ssb filter. Mixing this signal with the 455-kHz oscillator produces the audio output and components at 1100 kHz which are filtered out by the audio amplifier. The audio output is operator-controlled through adjustable volume and squelch pots.

In transmit, the microphone output is fed to a dual-purpose audio agc amplifier. First, it provides a rising characteristic to frequencies above 900 Hz for better intelligibility. Second, since the LEDs are peak-power-limited, the agc maintains a constant audio amplitude to prevent overmodulation. The audio then modulates a 455-kHz carrier to produce a double-sideband-suppressed carrier signal to the Collins filter. The upper sideband products mix with the 539-kHz oscillator to yield signals of 84 kHz and 994 kHz. Filtering leaves the 84-kHz ssb signal, which current-modulates the LEDs with a class C sinewave. This method of modulation achieves an optimum condition by giving the highest peak optical power for the least amount of current drain from the battery.

The Texas Instruments TIES16C LED was chosen as the infrared source because of its appreciable optical output power of 350 mW minimum and its hemispherical radiance pattern. Use of these LEDs greatly simplified the system optical design and minimized the power requirements of the battery pack. These diodes are commercially available and have an effective normal radiance of 80 mW/sr at the rated current of 3 A.

A TIES16C LED was mounted on a rotational mount and was power supply-driven at 1 A. The data were taken from a telescope-mounted photodetector to prevent background light from altering the data (as much as possible). The objective was to test a reflector which would give the desired irradiance pattern of 180° in azimuth and ± 30° in elevation. The reflector would also effectively double the output power in the designated beam pattern, as opposed to the LED pattern without a reflector (figure 5.5). These results are presented in table 5.1.

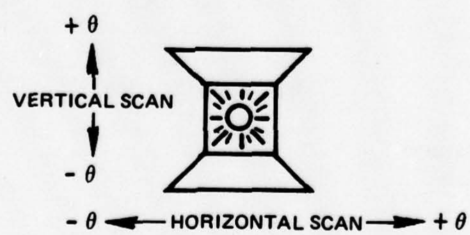


Figure 5.5. Data taken for LED pattern with and without reflector.

Table 5.1. Relative LED output as a function of scan angle.

Scan Angle, deg (Center Reference)	Vertical Scan, mW With Reflector	Vertical Scan, mW Without Reflector	Horizontal Scan, mW With Reflector	Horizontal Scan, mW Without Reflector
-120	- - -	*	0.04	0.04
-110	- - -	*	.04	.04
-100	- - -	*	.05	.06
-90	- - -	*	.06	.08
-80	- - -	*	.09	.11
-70	- - -	*	0.17	0.24
-60	- - -	*	.33	.36
-50	0.04	*	.41	.41
-40	.15	*	.65	.41
-30	.46	*	.70	.41
-20	0.75	*	0.71	0.41
-10	.73	*	.69	.41
0	.72	0.40	.71	.42
10	.75	.38	.72	.43
20	.74	.38	.73	.42
30	0.63	0.36	0.71	0.41
40	.12	.37	.58	.40
50	.04	.35	.41	.39
60	- - -	.34	.33	.31
70	- - -	.20	.18	.17
80	- - -	0.11	0.09	0.09
90	- - -	.07	.08	.08
100	- - -	.04	.06	.06
110	- - -	.04	.04	.04
120	- - -	- - -	.04	.04

Background = 0.04 mW

* Not measured
- - - Negligible

The data are retabulated in table 5.2 and normalized to the peak diode output without reflector to show the antenna gain. The data are also corrected for background irradiance.

Table 5.2 Normalized values of LED patterns.

Scan Angle, deg (Center Reference)	Vertical Scan, mW With Reflector	Vertical Scan, mW Without Reflector	Horizontal Scan, mW With Reflector	Horizontal Scan, mW Without Reflector
-120	---	*	---	---
-110	---	*	---	---
-100	---	*	0.026	0.051
-90	---	*	.051	.10
-80	---	*	.13	.18
-70	---	*	0.33	0.51
-60	---	*	.74	.82
-50	---	*	.95	.92
-40	0.28	*	1.56	.92
-30	1.08	*	1.69	.92
-20	1.82	*	1.72	0.92
-10	1.77	*	1.67	.92
0	1.74	0.92	1.72	.97
10	1.82	.87	1.74	1.00
20	1.79	.87	1.77	.97
30	1.51	0.82	1.72	0.95
40	0.21	.85	1.38	.92
50	---	.80	0.95	.90
60	---	.77	.74	.69
70	---	.41	.36	.33
80	---	0.18	0.13	0.13
90	---	.077	.10	.10
100	---	---	.051	.051
110	---	---	---	---
120	---	---	---	---

* Not measured
--- Negligible

These results are plotted in figure 5.6, along with the theoretical fit to the TIES16C relative intensity plot of $(\cos \theta)^{1/2}$. As can be seen from this plot, the design goal of the reflector, to double the output power into the forward lobe, has been achieved.

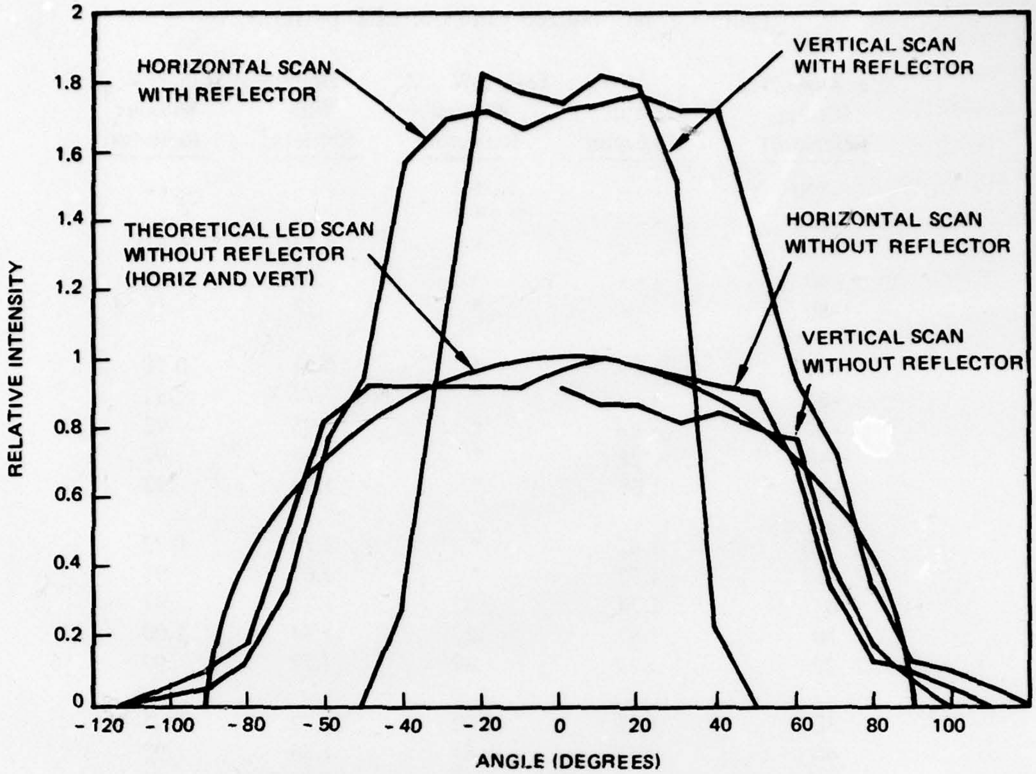


Figure 5.6. Relative LED output versus scan angle with and without reflector.

To evaluate the placement of the LEDs which would give an azimuthal coverage of ± 90° without much degradation to the optical power transmitted in the forward direction, a program was written to plot the beam pattern as a function of angular displacement of the LEDs, as shown in figure 5.7.

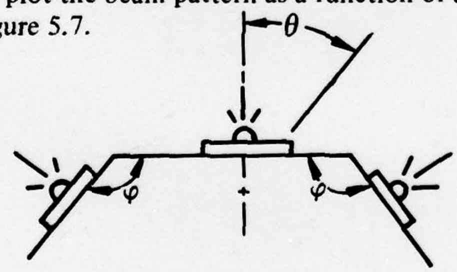


Figure 5.7. LED pattern used in computer model.

The theoretical azimuthal patterns are shown in figure 5.8. An angle of 120° was chosen for the UNREP system since it exhibited the desired beam pattern. The three-LED array was measured and, as can be seen in figure 5.8, the results closely match the theoretical model in the azimuthal direction. The anomalous double peak in the elevational plot in figure 5.9 results from the appreciable power content in the diode's output, which is doubly reflected.

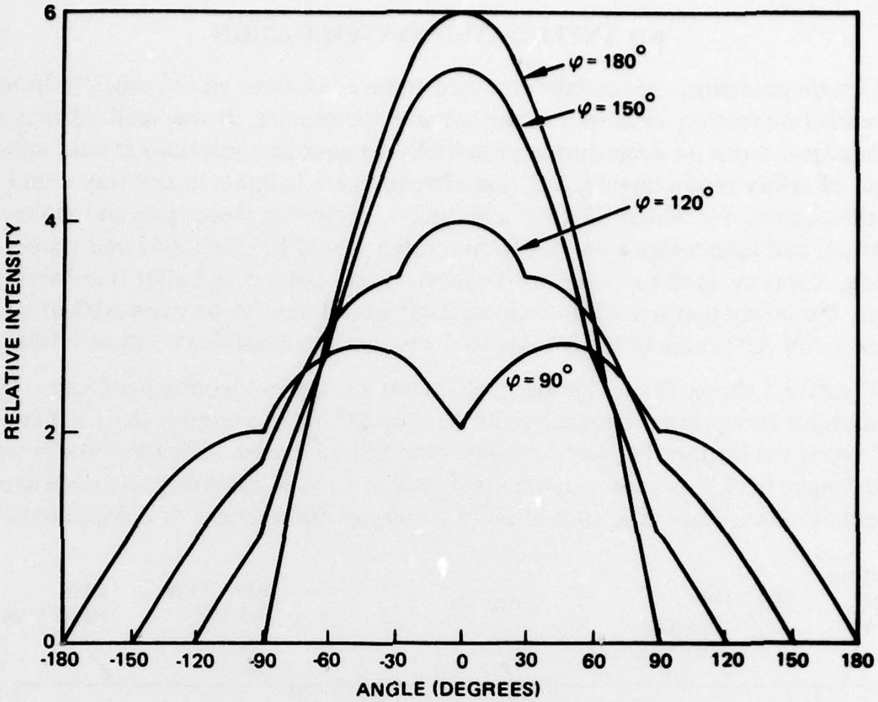


Figure 5.8. Azimuthal (θ) radiation pattern as a function of LED displacement (φ).

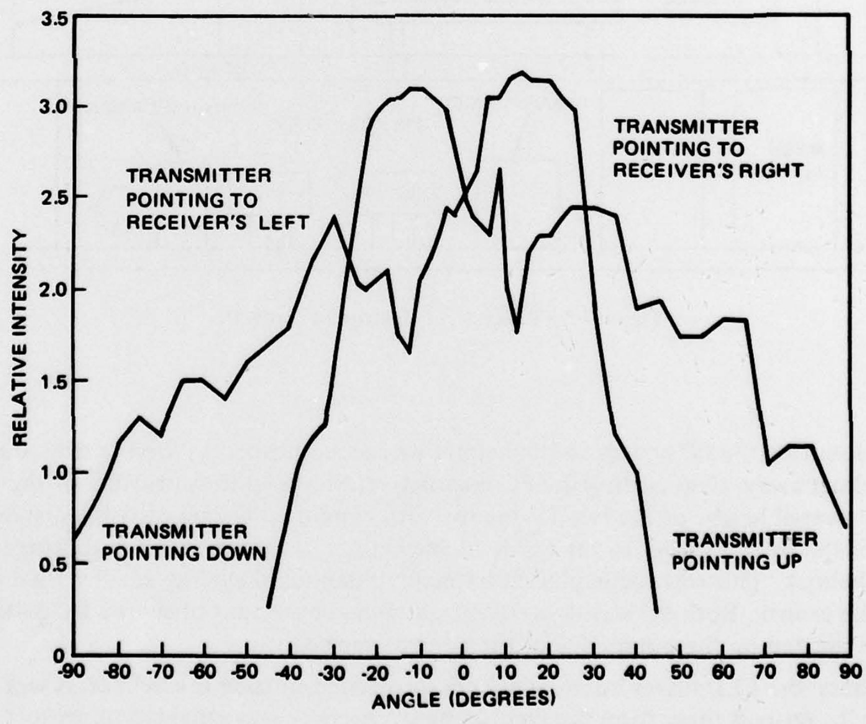


Figure 5.9. Three LEDs and three reflectors together.

6.0 INTEGRATED SYSTEM DESIGN

Certain guidelines and restrictions had to be considered in reference to human factors needs (see section 2) as well as the helmets themselves. It was realized that any type of headgear worn on deck during potentially hazardous operations should meet a certain set of safety requirements, and that altering these helmets in any way could destroy the purpose for which they were intended. However, since time and money were at a premium and fabricating a helmet from scratch would be too costly and time-consuming, it was decided to use an off-the-shelf safety helmet and alter it as needed. Therefore, the safety features of the helmet itself would have to be dealt with at a later date since RAPCAP's main objective was to demonstrate a feasible communications link.

Figure 6.1 shows the design package layout for the electronics hardware. The system contains two printed circuit boards; the top PC board contains the LED driver circuitry while the bottom PC board contains the SSB circuitry. The two boards were mounted "piggy back" by means of standoffs which allowed assembly and disassembly to the helmet as one piece, and thus allowed for easier replacement of components.

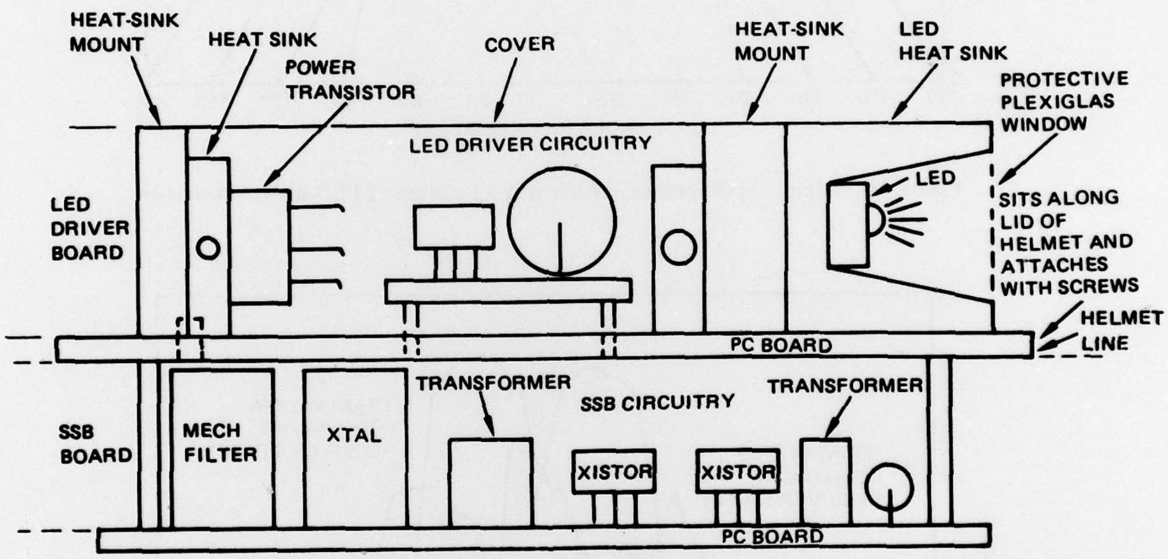


Figure 6.1. Package for electronics hardware.

Mounting the PC boards to the helmet was accomplished by first cutting the crown of the helmet away, then cutting the PC boards to conform to the curvature of the helmet. Since the overall height of the two PC boards with components exceeded the distance from the top of the wearer's head to the inside of the helmet, only the SSB board protruded into the helmet. This was accomplished by making the board slightly smaller than the hole in the crown. Both PC boards were then attached by means of screws to plastic standoffs located on the outer edge of the LED driver board.

Since the LED driver board and LEDs protruded outside the helmet, it was necessary to protect them from the environment. A cover was provided to protect the components on the PC board, while the LEDs were protected by a Plexiglas window that attached to the LED heat-sink mount. The transmittance of the Plexiglas window was tested and found to be 92–94% for the wavelength of 8500 Å–10 600 Å (near infrared).

Since the LEDs can draw up to 3 A average current apiece (three LEDs per helmet), heat sinking them and the power transistor was necessary. Figure 6.2 shows the configuration of the transistor heat sink and associated mount. Figure 6.3 shows the top view of the

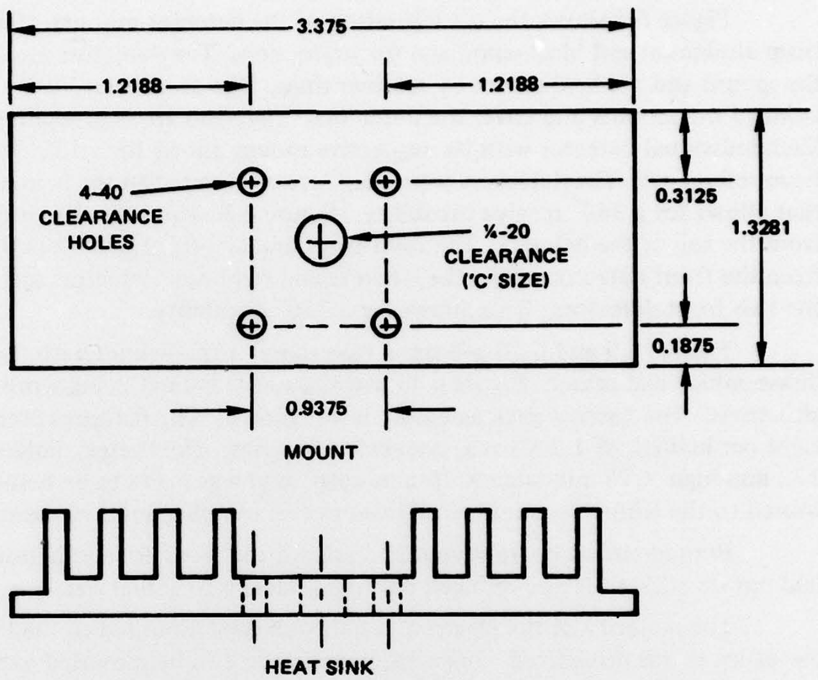


Figure 6.2. Transistor mount and heat sink (dimensions in inches).

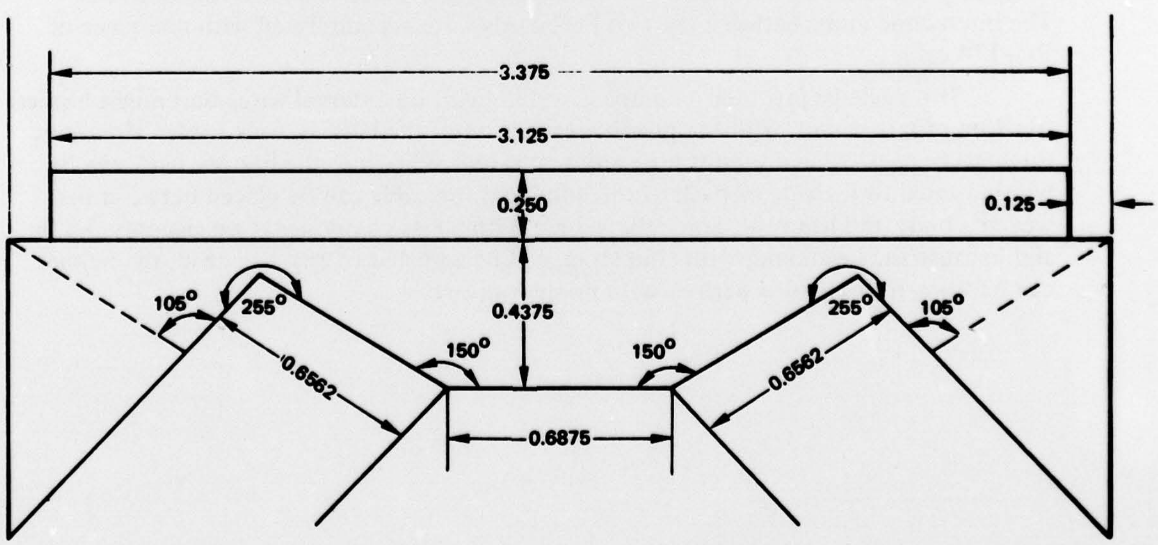


Figure 6.3. LED heat sink mount (Nylon)–top view (all dimensions in inches).

LED heat-sink mount. This configuration allows for a 180° azimuth transmission capability. Figures 6.4, 6.5, and 6.6 show three different views of the LED heat sink. This was made from aluminum, and the inside top and bottom faces were covered with polished aluminum to allow for a better reflective surface. Grooves were cut along the top to make a fin arrangement which allows for better heat dissipation. This configuration allows for a ± 30° elevation transmission capability.

Figure 6.7 shows the configuration of the detector mounts. These were made from aluminum and black-anodized for protection. The detectors are set into the back of the mount and are held secure by retainer rings. The absorption filters are set into the front of the mounts and cover the detectors. They too are held secure by retainer rings. Each individual detector with its respective mount allows for a 120° field of view (± 60° from reference). The detectors were then screw-mounted to the helmet in a configuration that allows for a 360° receive capability. Figure 6.8 shows the detector array (as viewed from the top of the helmet). The right-front and left-front detectors were mounted 50° from the front detector, while the left-rear and right-rear detectors are mounted 80° from the two front detectors. This allows for a 360° capability.

Figures 6.9 and 6.10 a–b show two views of the helmet with the hardware disassembled and intact. Figure 6.11 a–d shows the helmet being worn in actual work situations. The battery pack assembly is not shown. The batteries used were D-cells, eight per helmet, of 1.2 V each, connected in series. The battery holder has dimensions of 172 mm high X 76 mm wide X 76 mm deep* and was made to be belt-mounted. Power was routed to the helmet by means of a five-pin Cannon plug and a single-shielded cable harness.

Printed circuit board layout and fabrication were done in-house. The artwork was laid out on a 2X scale and reduced photographically to actual size.

The majority of the electronics hardware was mounted to the PC boards, so the use of wires was minimized. The hardware that had to be mounted external to the PC boards consisted of the photodetectors, microphone, on/off volume and squelch potentiometers, and the push-to-talk switch. The photodetectors were hard wired to the ssb preamp via #22 wire. The other controls were mounted to the earcup for easy accessibility and a single-shielded harness assembly was utilized for interconnections. The interconnections between the two PC boards were accomplished with one piece of RG–174 cable.

This package provided a compact system with no external wires that might hinder freedom of movement, with the possible exception of the battery pack cable. However, the battery pack cable does not pose any real problem because the battery pack can be belt-mounted to the side or back of the body and the cable can be placed between the wearer's body and life vest. Since the helmet with all its components weighs only 3.5 lb, and because the headband, with chin strap, can be adjusted to any size head, the helmet can be worn for extended periods with no discomfort.

---

*6.75 X 3 X 3 inches.

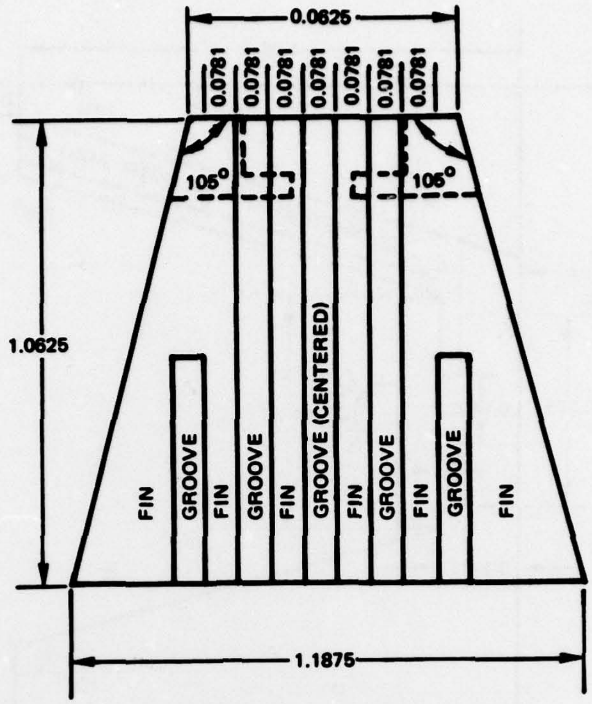


Figure 6.4. LED heat sink (aluminum)–top view (all dimensions in inches).

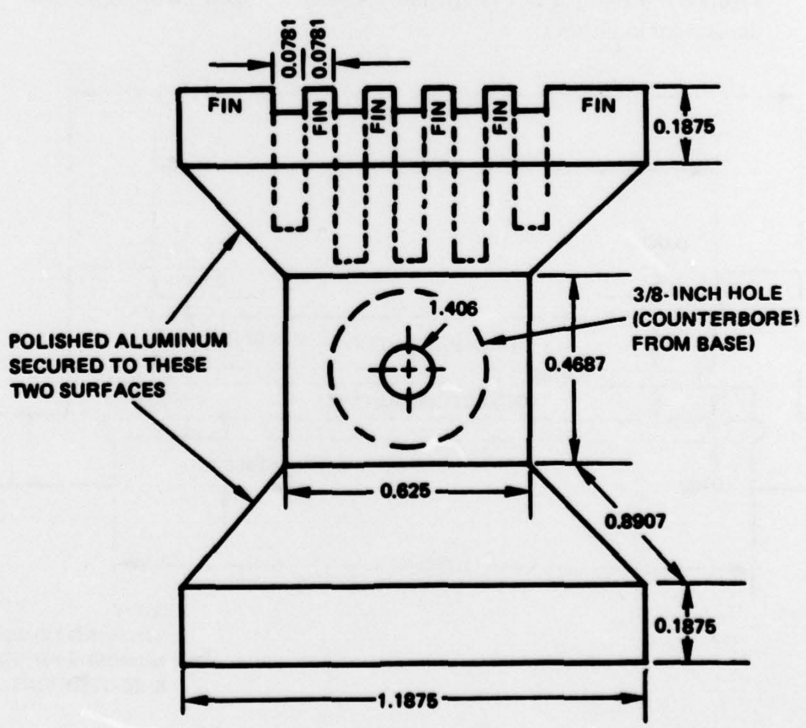


Figure 6.5. LED heat sink (aluminum)–front view (all dimensions in inches).

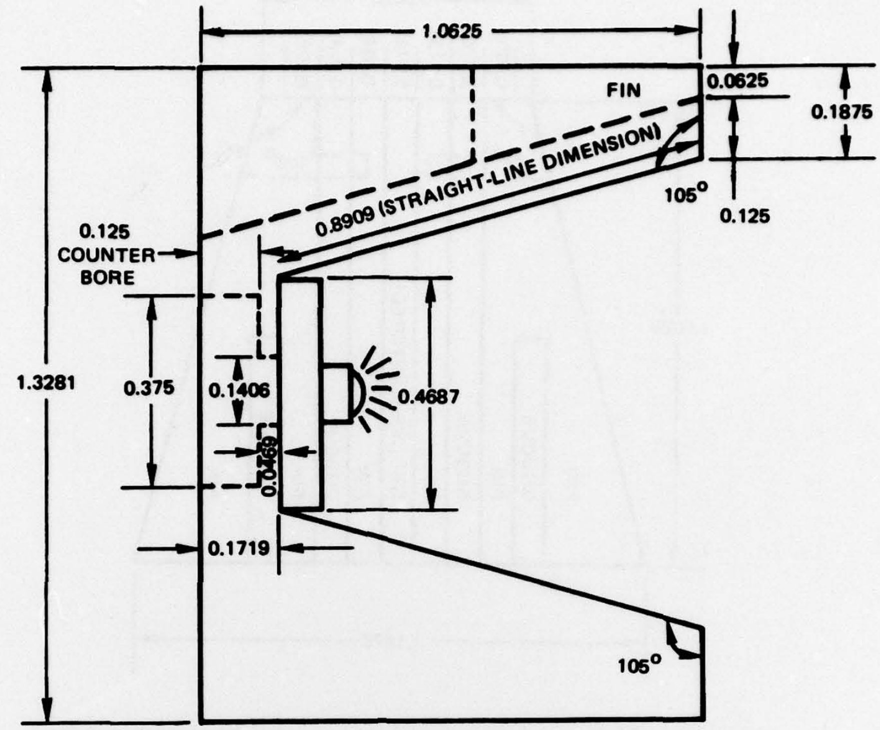


Figure 6.6 LED heat sink (aluminum)–side view. Shown with LED. (All dimensions in inches.)

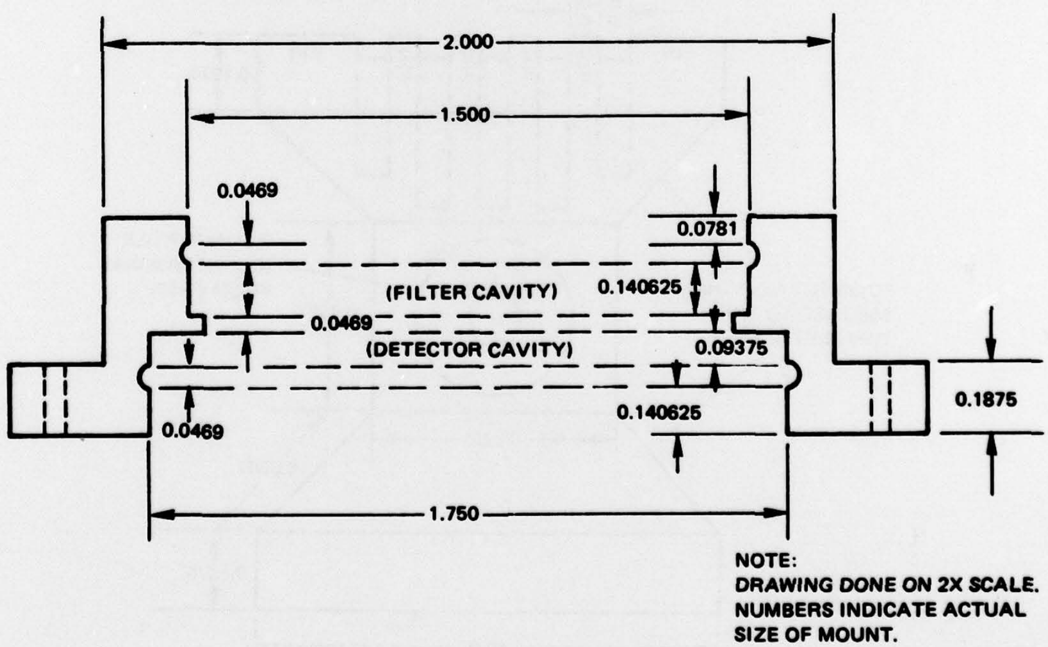


Figure 6.7. Filter/detector mount, side view. (All dimensions in inches.)

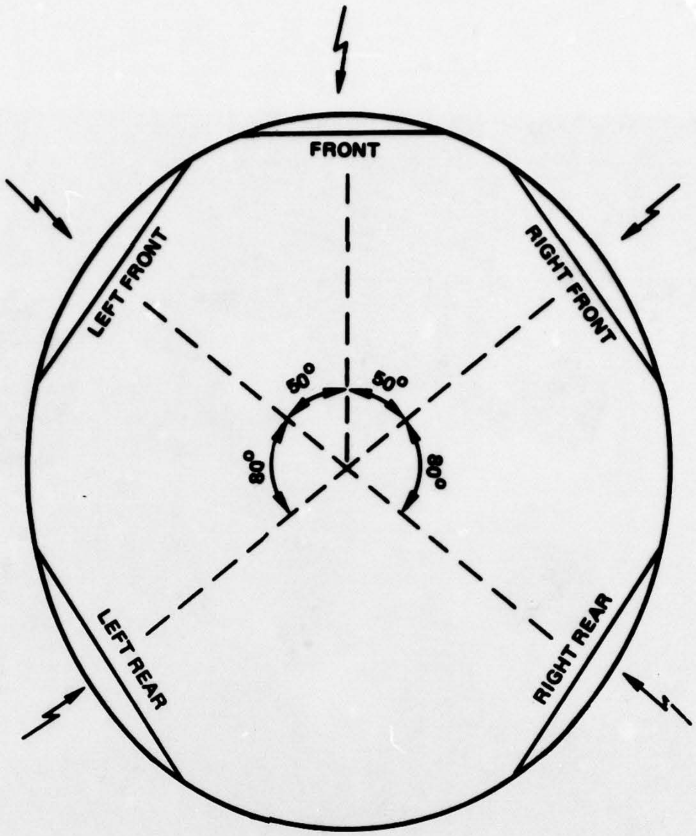


Figure 6.8. Detector array—top view.

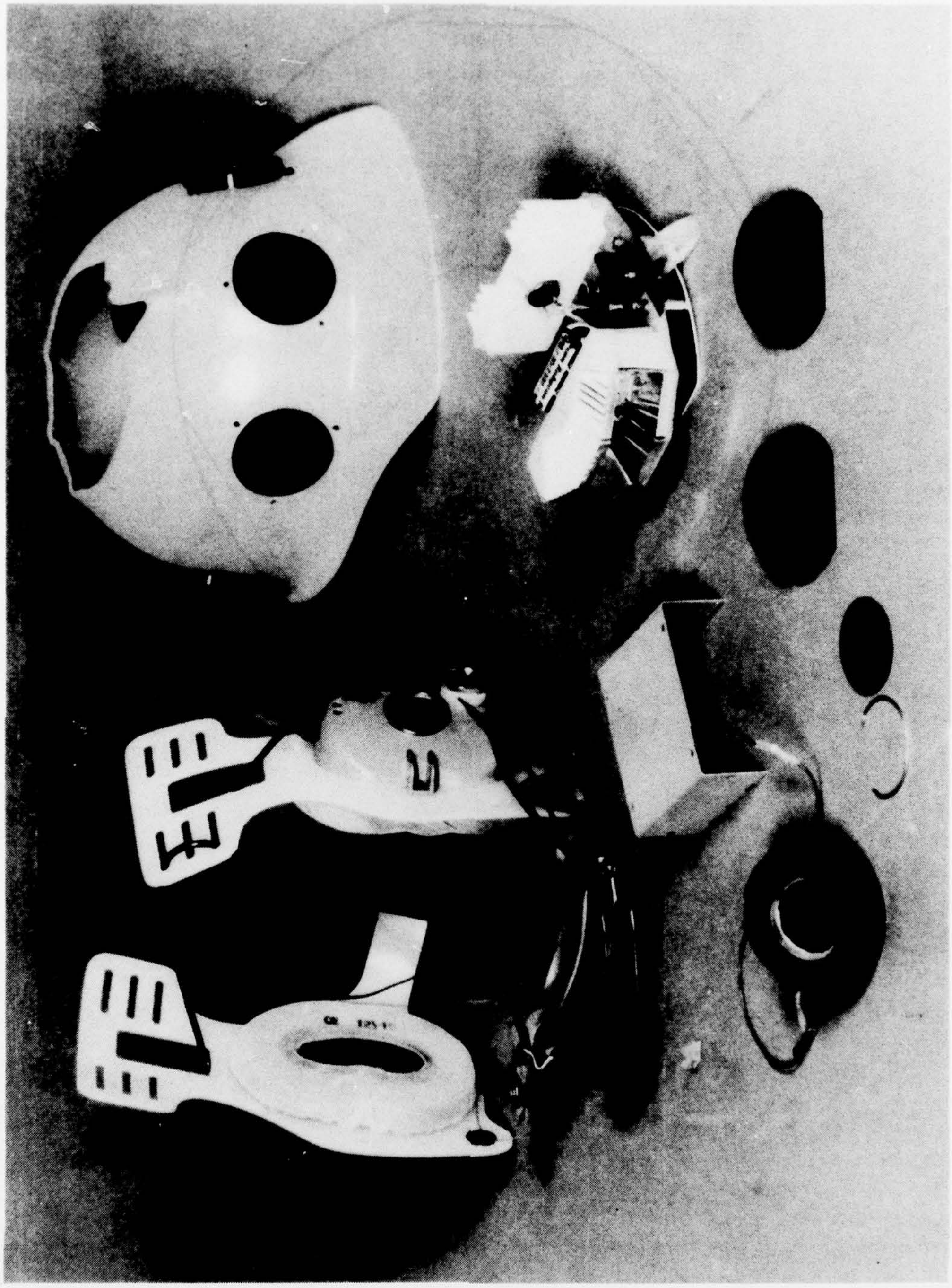
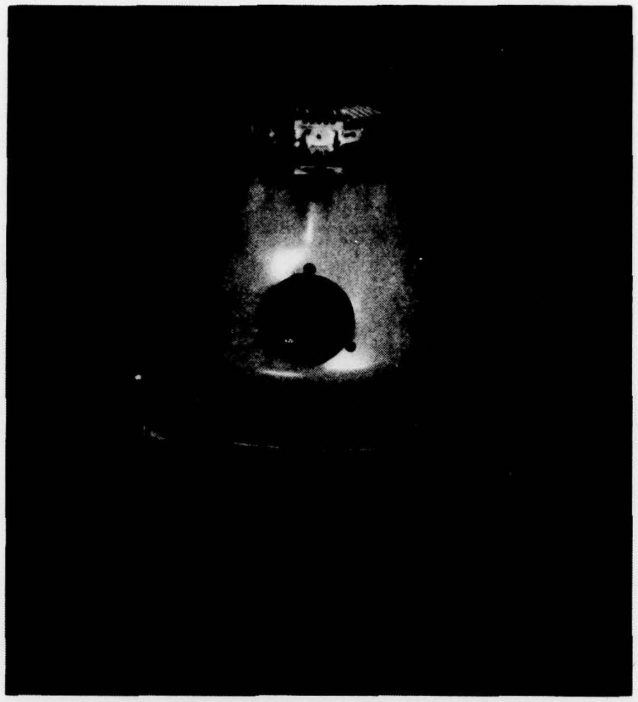
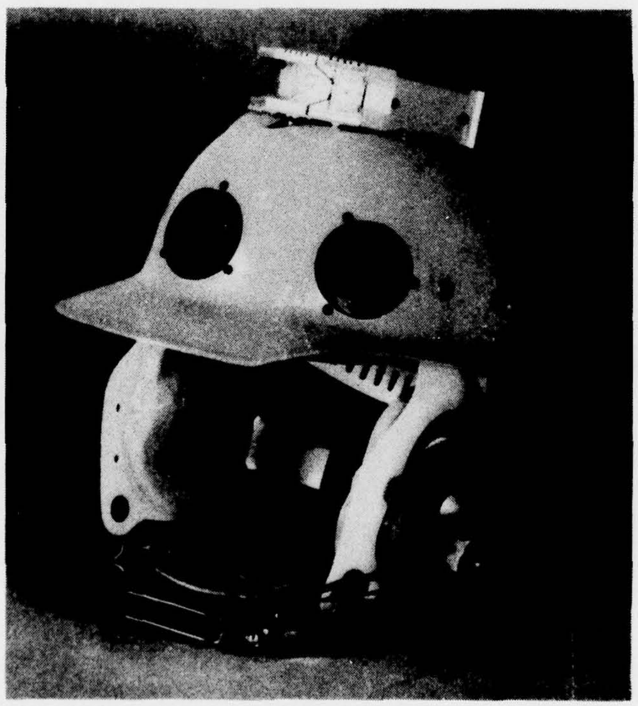


Figure 6.9. Disassembled helmet.

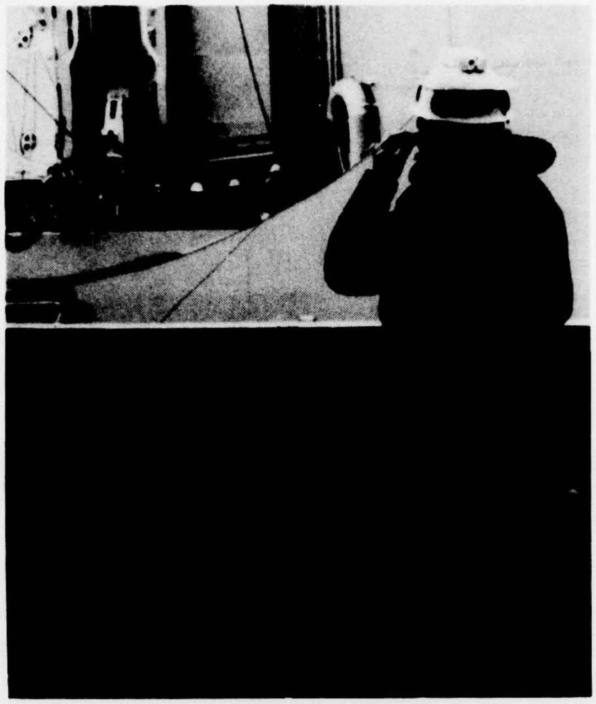


(a)



(b)

Figure 6.10a-b. Completed helmet.



(a)

(b)

Figure 6.11a-b. Helmet being worn in work situations.

(c)

(d)

Figure 6.11c-d. Helmet being worn in work situations.

7.0 PERFORMANCE RESULTS

Three brassboards for the RAPCAP helmet communicators were tested at NOSC for performance. The audio quality of voice communications was measured by the modified rhyme test (MRT) at three operationally significant ranges of 35, 70, and 100 metres. The tests were conducted outdoors under thinly clouded sky and again under hazy overhead sunlight conditions. A Navy enlisted man transmitted a 50-word list to another enlisted man directly facing the transmitter. Figure 7.1 shows an average score of 70 in these tests for three different RAPCAP helmets. A score of 70 on the MRT is usually interpreted as

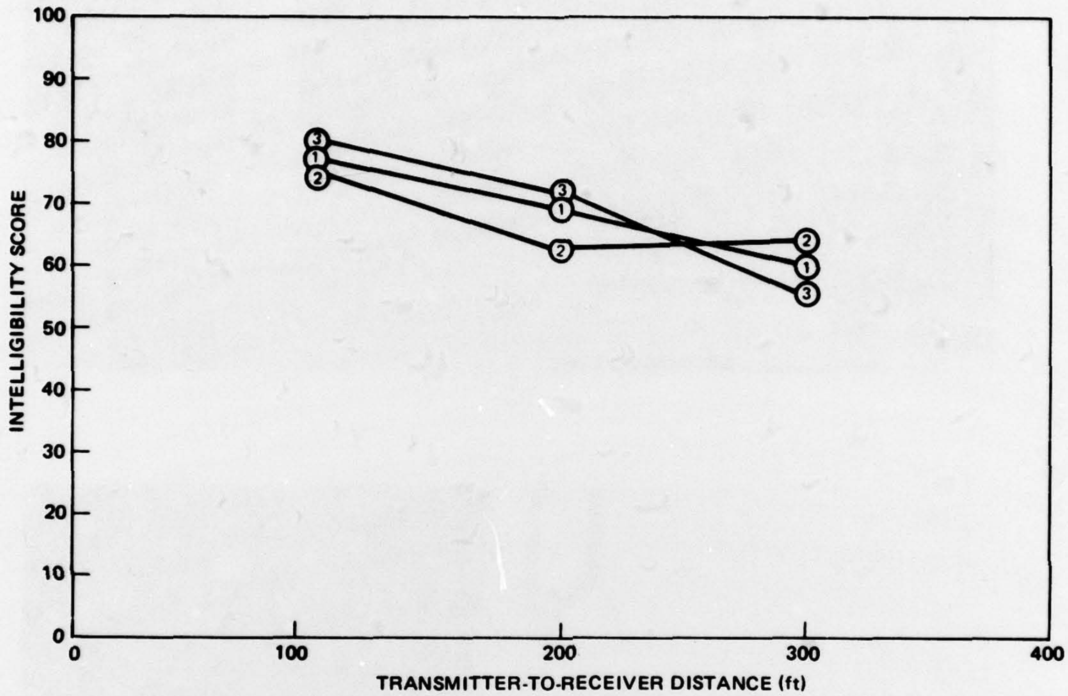


Figure 7.1. RAPCAP voice intelligibility test curves.

most standard messages understood, with occasional requests for message repeats. Non-standard or unusual messages are marginal to difficult to receive. These average test scores indicate performance levels sufficient to demonstrate the RAPCAP concept. The speech bandwidth was limited to 2.4 kHz and that factor was felt to severely restrict overall intelligibility. Many techniques and hardware are being developed to compress speech bandwidth and still achieve a high degree of intelligibility. It is expected that a system using the RAPCAP concept will benefit greatly from these developments. NOSC conducted the first sea demonstrations of the RAPCAP helmet communications system during June 1978. These demonstrations were successfully accomplished during underway replenishment exercises off the southern panhandle of Alaska between the USS SACRAMENTO (AOE 1) and the USS HOOD (AE 29).

NOSC had two objectives in participating in UNREP exercises under operational conditions. The first was to perform a realistic demonstration for the Navy of a direct, wire-free, man-to-man communications system capable of unrestricted use during EMCON conditions. The second was to evaluate the utility and performance of the RAPCAP helmet experimental configuration and to ascertain human factors and needed design improvements for follow-on developmental efforts. Both objectives were met and the results achieved the goals of this program.

During the demonstration, the rig captain for an UNREP transfer station on each ship was outfitted with a RAPCAP helmet (figures 6.11 a – d). The unit provided the rig captain with real-time, wire-free communications (WFC) to the other vessel's rig captain during all EMCON conditions. This capability was shown to contribute significantly to safety, effectiveness, and manpower reduction for each UNREP evolution. During the test period, the RAPCAP system was used by nine different rig captains during 10 UNREP evolutions. These UNREPs included dummy and real loads for both liquid and dry cargo during day and night operations. An evaluation from the commanding officer of the USS SACRAMENTO states in part, ". . . the most important aspect (of RAPCAP) is direct operator communications, saving time and ensuring good communications by eliminating an often inexperienced man who does not always understand the process or the terminology. Delays and other problems during the transfer can be solved much more rapidly and efficiently by the personnel in charge of the operation talking to each other directly."