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Intentionally Short-Range Communications (ISRC) Exploratory Development Plan

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NAVAL COMMAND, CONTROL AND OCEAN SURVEILLANCE CENTER RDT&E DIVISION
San Diego, California 92152-5000

J. D. FONTANA, CAPT, USN
Commanding Officer

R. T. SHEARER
Executive Director

ADMINISTRATIVE INFORMATION

This work was conducted during FY 91-92 under project C3125, Command Control and Communications mission area. The work was funded under program element 0602131M and performed for the Director, Amphibious Warfare Technology Directorate (Code AW), Marine Corps Systems Command, Quantico, VA 22134.

Released by
D. M. Gookin, Head
Electro-Optic Devices
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C. E. Gibbens, Acting Head
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SUMMARY

OBJECTIVE

Establish a comprehensive exploratory development plan for the Intentionally Short-Range Communications (ISRC) project. This plan should develop possible solutions for all three U.S. Marine Corps tactical communications requirements.

RESULTS

1. Developed an exploratory development plan for each of the three USMC requirements, namely Company Radio, Local Area Network Backbone and Wideband Link. These plans are consolidated in this document.

2. Selected and awarded Phase I Small Business Innovation Research (SBIR) contract to explore options based on ultraviolet (UV) lamps.

3. Evaluated and selected Phase I Broad Agency Announcement (BAA) contracts to explore options based on UV laser, infrared (IR) laser, and millimeter wave (MMW).

4. Proceeding with fabrication of a tunable intracavity-tripled Ti:Sapphire laser to generate UV radiation.

5. Proceeding with fabrication of a one-way UV laser link to test propagation and noise characteristics.

RECOMMENDATIONS

1. Continue to monitor the SBIR and BAA phase I contracts and prepare to downselect for Phase II.

2. Complete and evaluate the Ti:Sapphire laser cavity.

3. Complete and test the simplex UV laser link. Analyze the resulting data to determine link feasibility for proceeding to a duplex UV laser link.

CONTENTS

FIGURES

TABLES

1.0 ADMINISTRATIVE INFORMATION

1.1 PROJECT NUMBER/MISSION AREA

C3125/Command control and communications.

1.2 PROGRAM ELEMENT NUMBER/TITLE

602131M/Marine Corps Landing Force Technology.

1.3 PERSONNEL

Mr. Kevin Smith, Marine Corps Systems Command (MCSC), Amphibious Warfare (Code AW) Directorate, (703) 640-2761, AV 278-2761.

Mr. John Yen, Naval Command, Control and Ocean Surveillance Center, RDT&E Division (NRaD) [formerly the Naval Ocean Systems Center (NOSC)], Code 843, (619) 553-6502, AV 553-6502.

1.4 ACQUISITION REVIEW CATEGORY (ACAT)

Non-ACAT.

1.5 DEVELOPMENT PROGRAM TYPE

Joint USMC/USN.

2.0 DEVELOPMENT PLAN

2.1 OBJECTIVE

The purpose of the USMC Intentionally Short-Range Communications (ISRC) Exploratory Development project is to demonstrate the feasibility of using one or more technologies for short-range data transmissions.

A satisfactory technology will be range-limited based on the physical properties of the atmosphere and the propagation medium. Thus, the link has an inherent low probability of direction finding (LPDF).

2.2 SCOPE

This plan encompasses the development, fabrication, and testing of several candidate technologies for all three of the ISRC links: Company Radio, Local Area Network (LAN) Backbone, and Wideband Link.

This plan also includes in appendix A the test requirements, or protocols, that each of these links must satisfy to be considered a viable system.

3.0 BACKGROUND

3.1 INTRODUCTION

The USMC has expressed interest in developing short-range communications links whose ranges are intentionally limited to very short distances. These links are described below and their architecture is shown in figure 1. This document is a development plan for the feasibility study of all three ISRC links. The Company Radio and the LAN Backbone links were previously studied in informal interim plans, which will now be incorporated into this overall exploratory development plan.

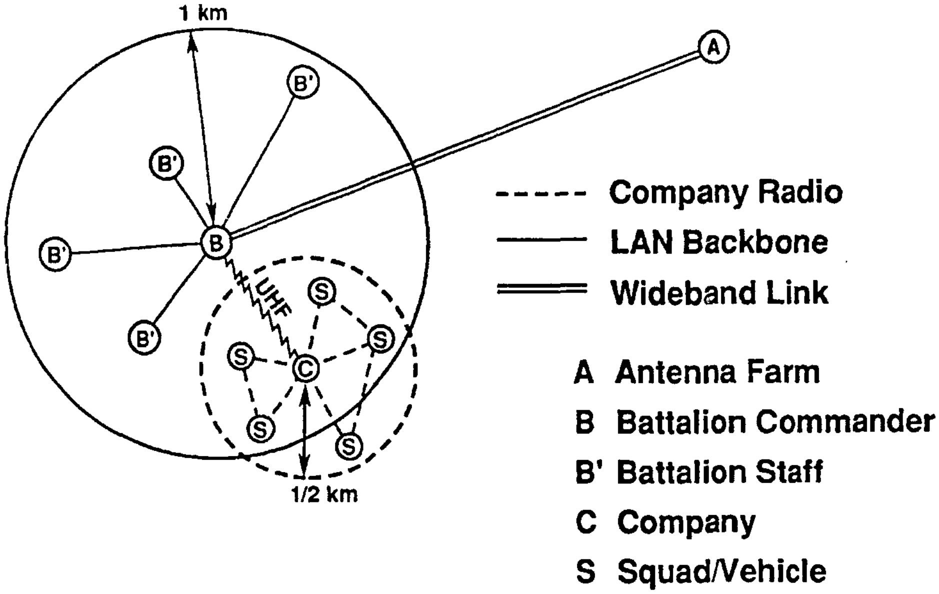

Figure 1. ISRC architecture.

3.1.1 Company Radio

Very short range (≤0.5 km), omnidirectional, low-data rate (2400 bps), vehicle-mounted, mobile, voice link for use by several squad leaders of a company. Figures 2 and 3 show two possible applications of the Company Radio, in an urban warfare scenario and as a landing zone communicator.

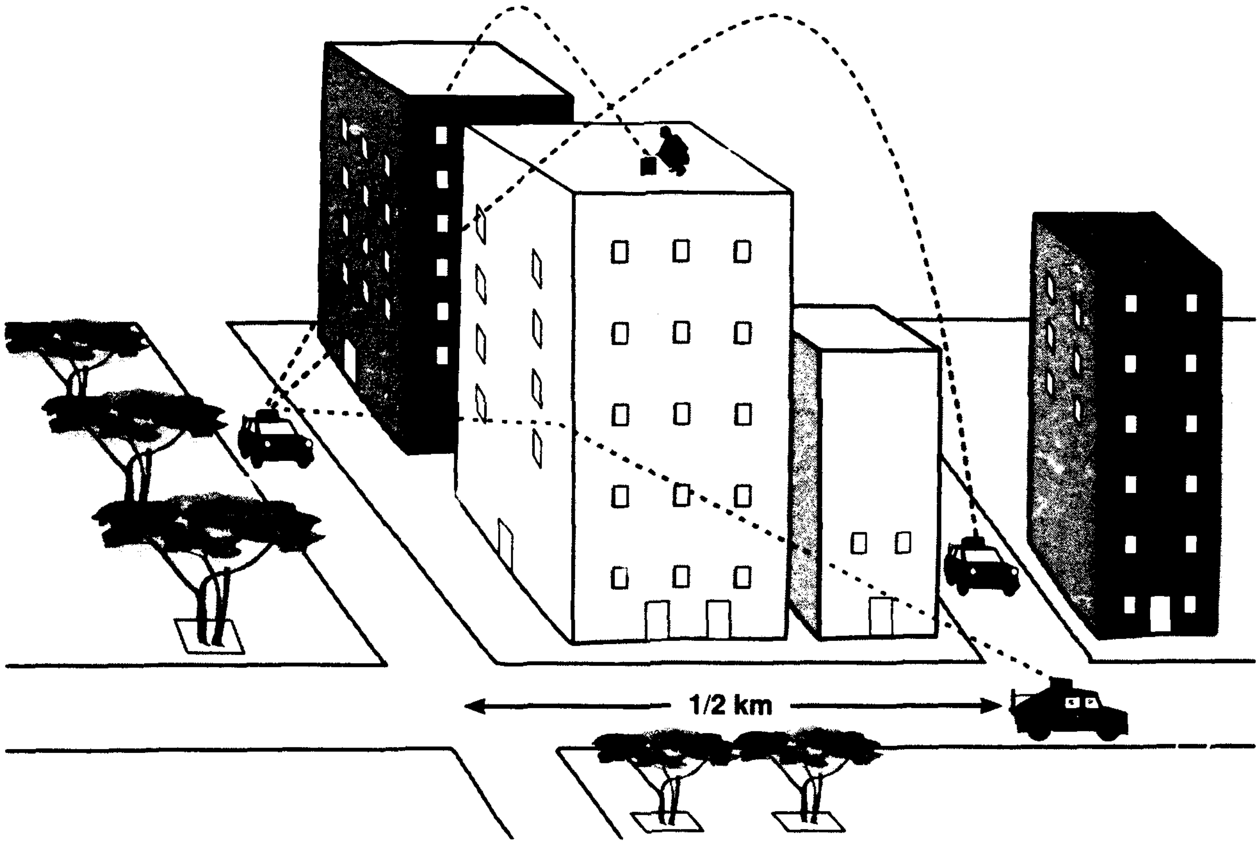

Figure 2. ISRC Company Radio: urban warfare.

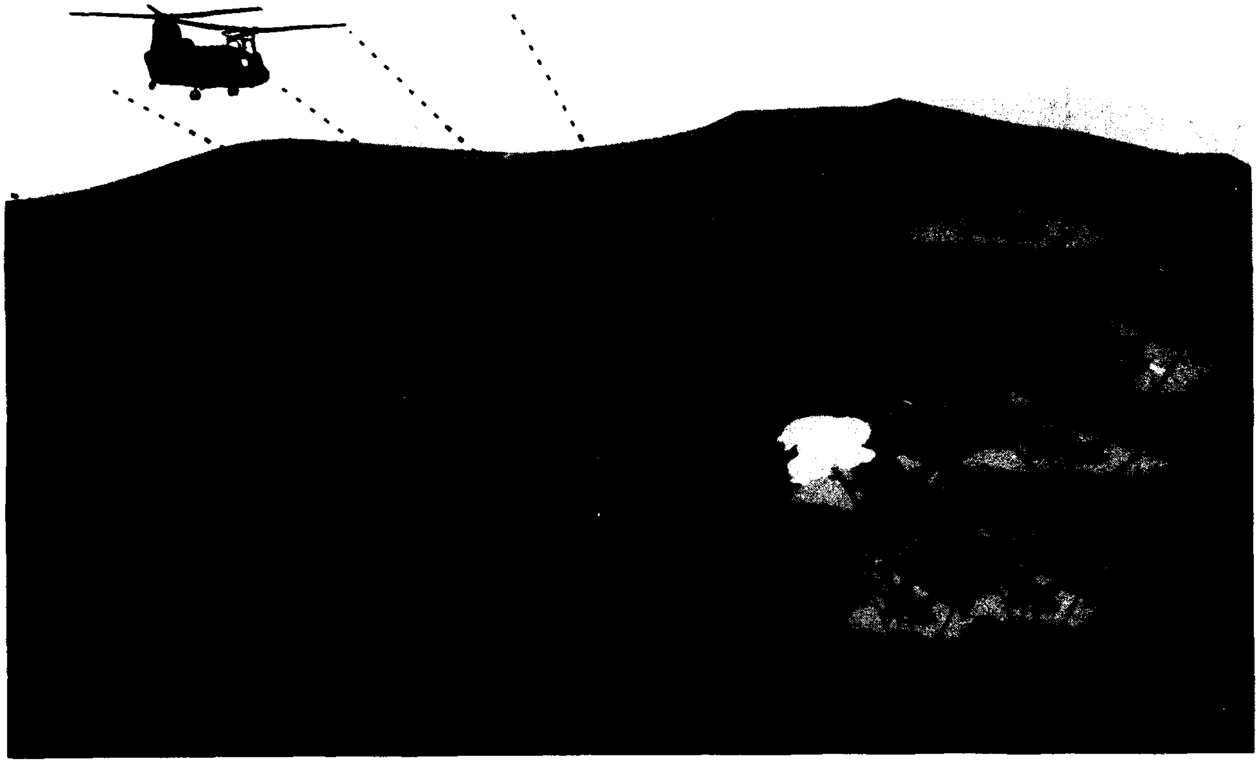

Figure 3. Intentionally short-range communications (IRSC) landing zone communicator.

3.1.2 LAN Backbone

Short-range (≤1.0 km), semidirectional, low- (2400 bps) to high- (2 Mbps) data rates, transportable, data link for connecting the battalion commander and his staff in a local area network (LAN). The LANs range from the low-data rate Banyan VINES to high-data rate full LANs and wide-area networks (WAN). Figure 4 is a graphical representation of the LAN Backbone.

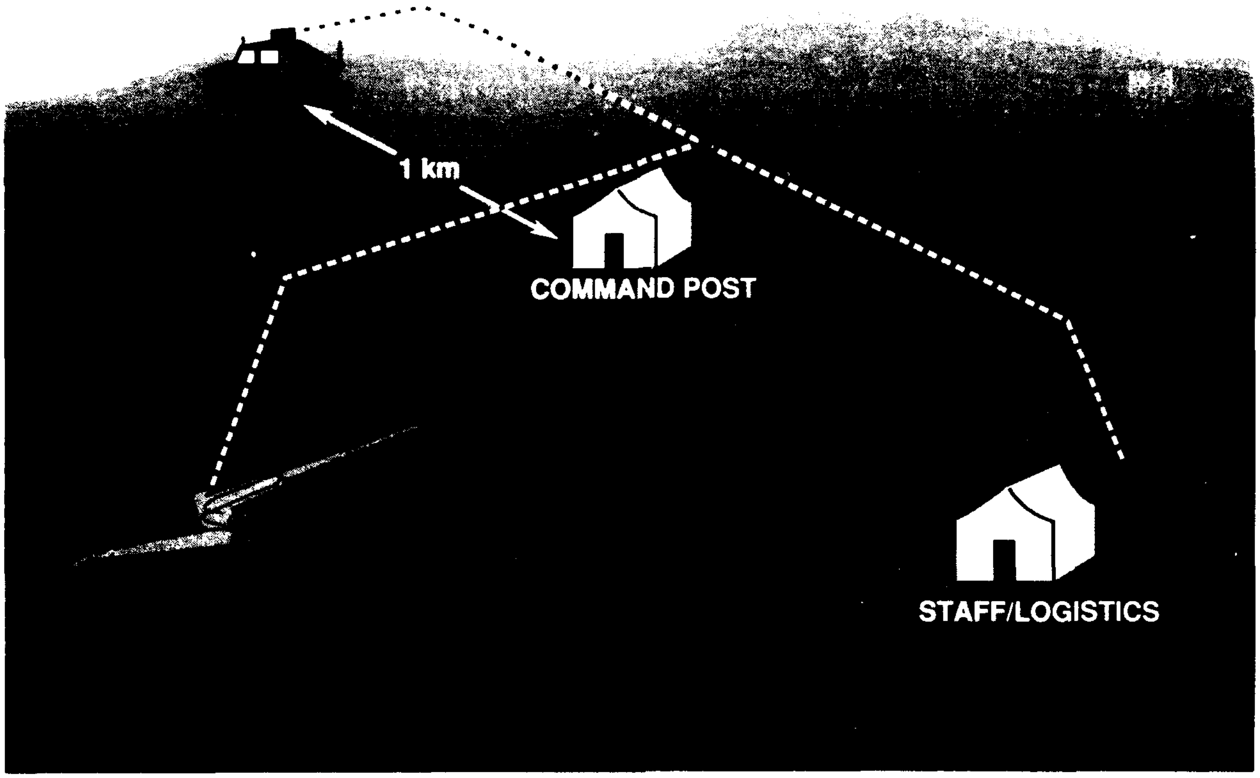

Figure 4. Intentionally short-range communications (ISRC) LAN backbone.

3.1.3 Wideband Link

Medium-range (3–5 km), directional, vehicle-mounted or fixed, high-data rate and traffic (2 Mbps) link for connecting command posts (CPs) with the antenna farm, as represented by figure 5.

3.1.4 Signal Detection

Most current communication systems (such as radio) have the r^{-2} signal attenuation associated with electromagnetic radiations. This means that while the enemy cannot understand our (encrypted) transmissions, he can still detect their presence and direction find (DF) on them. This is a tactical threat to our forces.

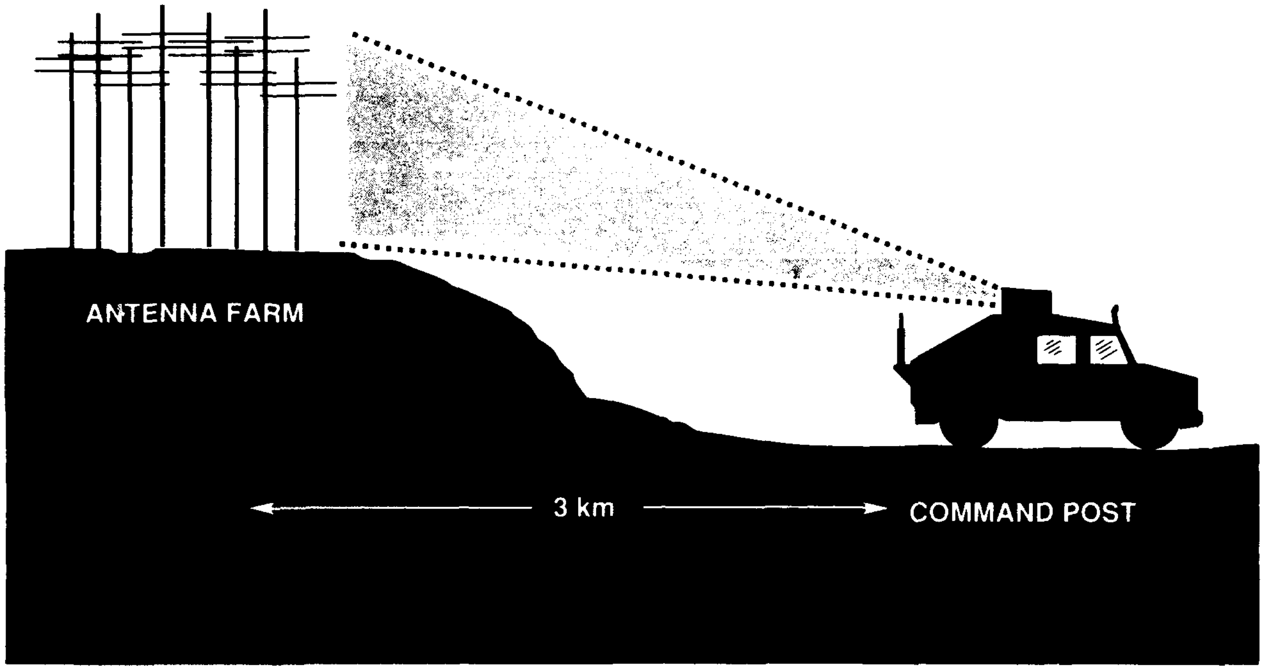

Figure 5. Intentionally short-range communications (ISRC) wideband link.

3.1.5 ISRC Terminology

3.1.5.1 Link Definitions. The link type definitions as used in this report are as follows:

Omnidirectional -	the signal is sent in all directions azimuthally
Semidirectional -	the signal is sent into an azimuthal quadrant (±45 degrees)
Directional -	direction is within ±5 degrees
Line-of-sight (LOS) -	within ±1 degree
Strictly LOS (SLOS) -	within ±0.01 degree
Non-LOS (NLOS) -	no LOS between the transmitter and the receiver

3.1.5.2 LPI and LPDF. Low probability of intercept (LPI) is taken here to mean that the enemy has a low likelihood to intercept and decode our transmissions. A system that is encrypted is LPI but still detectable by the enemy.

Low probability of direction finding (LPDF) is defined here to mean that the enemy has a low likelihood to detect our transmissions and direction find on them. An LPDF system is inherently LPI.

3.1.5.3 Broadband and Wideband. In this document, "broadband" is defined as a broad spectrum of wavelengths, as distinguished from "wideband," which is defined as a wide range of data rates. The following sentences are examples of these terms.

A broadband lamp emits wavelengths ranging from the infrared to the ultraviolet.

A wideband communicator can handle data rates ranging from a few kilohertz to many megahertz.

3.2 RESOLUTIONS

A tactical communications link whose range is limited physically by its atmospheric propagation characteristics will not be detectable outside of a limited range. Such a self-limiting link will then be a low probability of direction finding (LPDF) system.

Data encryption is still useful as added security within the operational envelope of the system.

There are at least three media in which the link range is limited by the propagation physics: ultraviolet (UV) light, infrared (IR) light, and millimeter waves (MMW).

3.2.1 Ultraviolet Sources

Ultraviolet (UV) light in the solar-blind spectral region (250–300 nm) is strongly attenuated by ozone molecules in the atmosphere (see figure 6 [Yen, 1987a]). The ozone layer in the upper atmosphere absorbs essentially all of the solar UV radiation in the solar-blind region, so that there is almost no solar background in this spectral region (see figure 7 [Yen, 1987a]). This low background allows the use of a very small number of received photons for a viable signal, resulting in a non-line-of-sight (NLOS) link.

Attenuation by the residual ozone at sea level (5–25 dB/km, depending on the ozone concentration) limits the range of a UV link to several ($\leq$5) kilometers. The ozone attenuation of UV radiation also limits the detection of UV transmissions to short distances, resulting in a covert or LPDF link. Figure 8 shows a graphical representation of the NLOS UV communications concept.

Given a receiver filter that transmits only in the solar-blind region and blocks all other radiations, a UV link can operate with very small received signals due to the lack of solar noise.

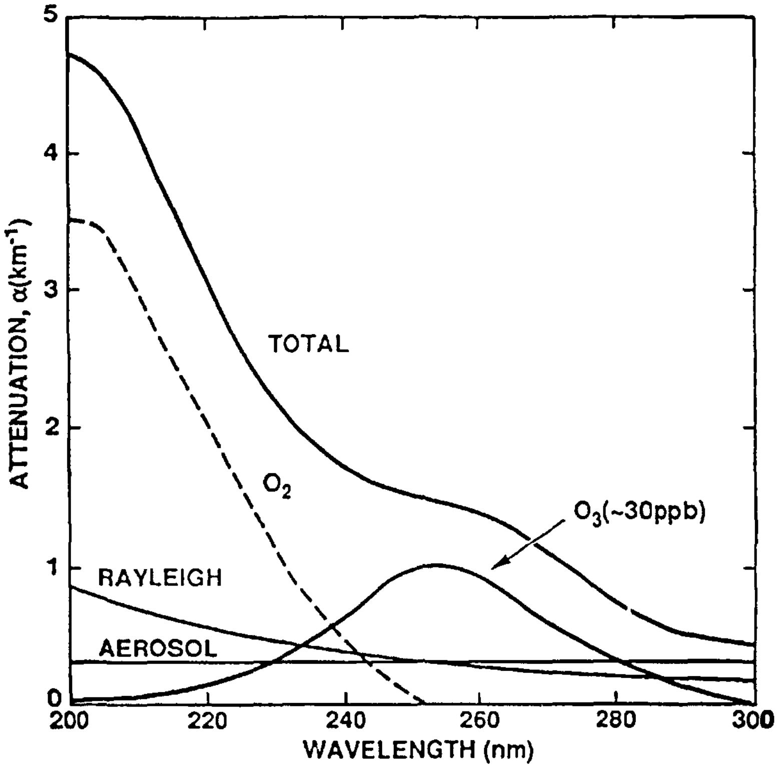

Figure 6. Sea-level extinction coefficients.

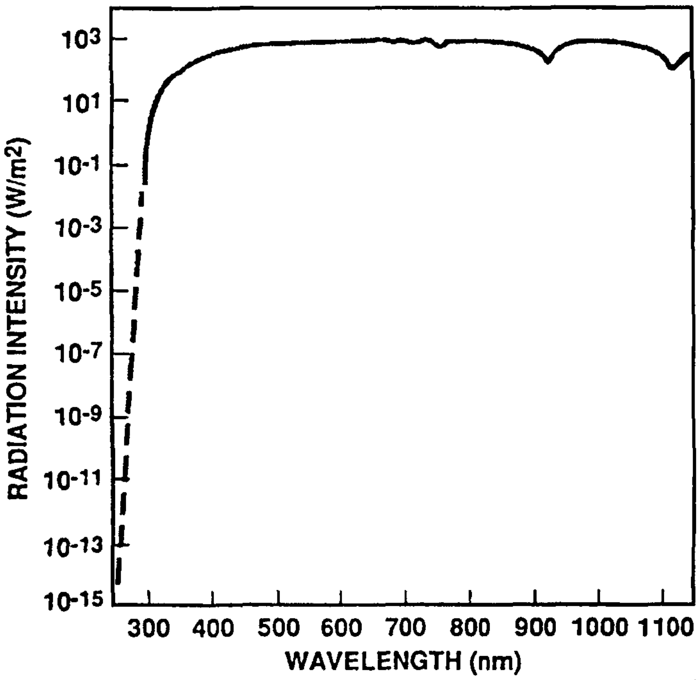

Figure 7. Solar radiation at sea level.

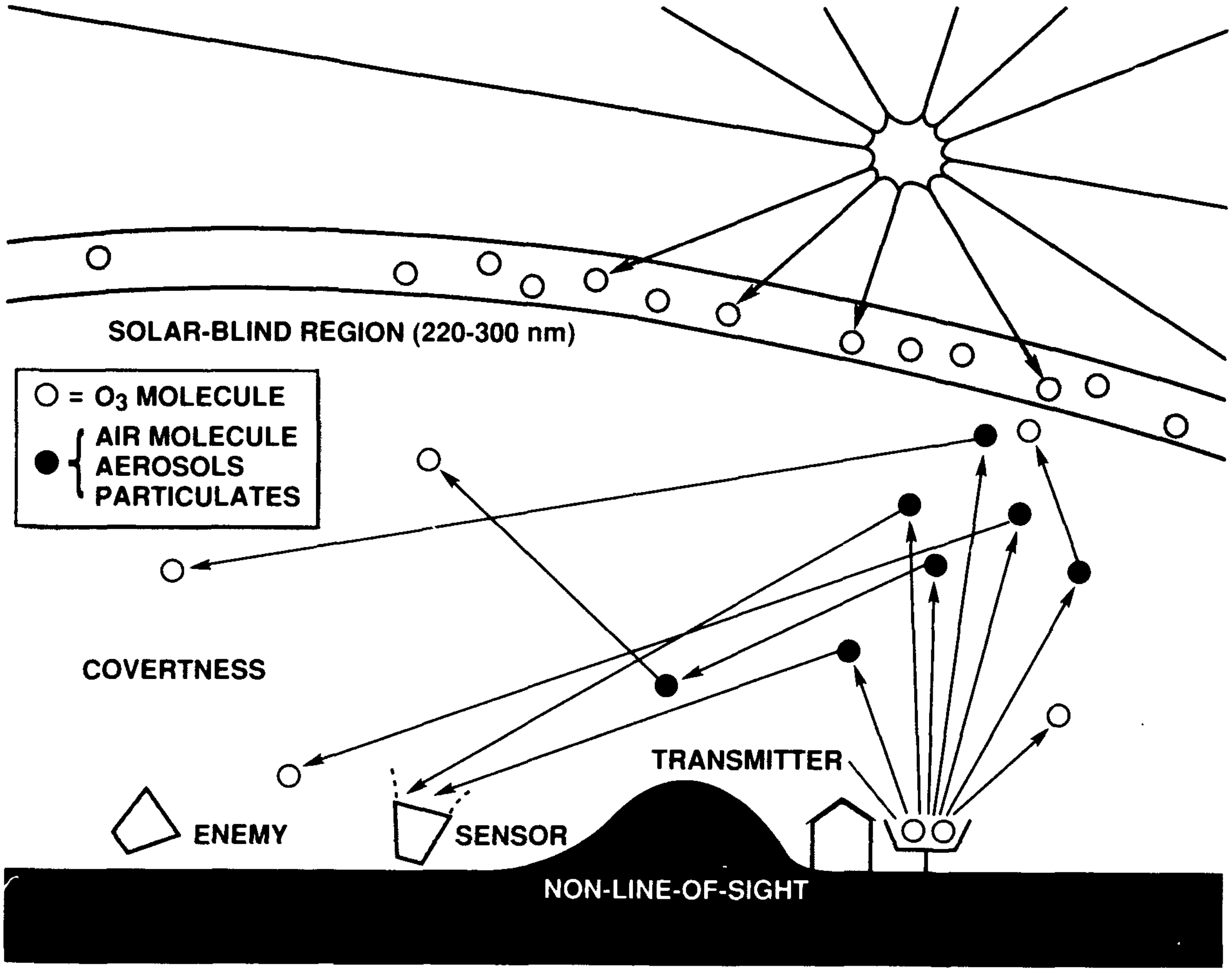

Figure 8. NLOS UV communications.

3.2.1.1 History. Communications using ultraviolet light in the solar-blind region was first proposed in the 1970s [Sunstein, 1968; Reilly, 1976; Kolosov, Pozhidayev, and Fedorova, 1976; and Junge, 1977]. In the late 1970s, the Army [Ross, 1978] and the Navy [Fishburne, Neer, and Sandri, 1976; and Neer and Schlupf, 1978] did early development work with broadband UV lamps for short-range voice communication links.

In the 1980s, NOSC developed a short-range, 2400-bps, computer-to-computer link for the USMC (UV Communications, or UV Comm [Geller, Johnson, and Shimabukuro, 1983; Johnson, 1986; Yen, 1987a]).

Concurrently, NOSC developed for the Navy a short-range, 2400-bps, data link (UV CAINS) to transfer Carrier Aircraft Inertial Navigation System (CAINS) data from the carrier to its aircraft [Nuyda, 1986; Yen, 1987a]. Both of these NOSC links used single-wavelength germicidal lamps for the UV transmitters.

Next, NOSC studied for the USMC the feasibility of UV radiation for longer range links (Yen and Moberg, 1988). This study indicated that some disadvantages must be resolved to make a UV link practical. The NOSC UV Communication link was subject to interference by fires, flares, explosions, welding, and lightning, so procedures must be implemented to deal with them. Heavy fog, smog, rain, and smoke also can limit the link distance below that required.

Currently, NRaD is performing a feasibility study of the ISRC LAN Backbone and Company Radio based upon a UV laser. The pulsed-laser approach was adopted in part to achieve tunability and noise suppression. With certain types of lasers, the wavelength can be varied, or tuned. The short, but sharp pulses of a laser may resolve the above-mentioned noise problem.

3.2.1.2 UV Sensor. To take advantage of the solar-blind region, the receiver filter must be able to block non-solar-blind radiation very effectively. The Honeywell filter that was used for UV Communications was too expensive (≈$10K per unit) for mass use as in the voice and data links. There are less expensive, but less effective, filters available commercially. These commercial filters would require stronger signals to overcome greater background leakages.

The photomultiplier tube (PMT) used in the UV Communication sensor is highly sensitive, but it is also expensive. If the received signal can be boosted significantly, then it may be possible to use lesser quality PMTs, which are less sensitive, but much cheaper and may be smaller. The currently used PMTs have a dead time that is of the same magnitude as the laser pulsewidth, which may be problematical for the near field (where the UV photons will not have been scattered enough to achieve a sufficiently wide time spreading).

Solid state UV detectors, while cheaper and smaller, have sensitivities that are orders of magnitude less than PMTs. To effectively use solid state detectors, the signal strength must be increased accordingly, which is not practical with current technology.

3.2.1.3 UV Lamp. The UV source (germicidal lamps) used by the UV Communication system was highly efficient in outputting UV light at a single wavelength (254 nm). However, it was bulky, fragile, and restricted in data rates ($\leq$20 KHz at shorter ranges). Therefore, it is not recommended for use in the ISRC links with higher data rates.

Arc lamps are compact and easier to harden, but they are broadband optical emitters, thus making them difficult to use for multichannel applications. Their output power is also not sufficient for some of the ISRC links. Finally, their IR and visible emissions can prove a detection signature unless filtered out.

UV lamps would be the easiest and least expensive to adapt for use in the low-data-rate links. This avenue would be desirable for building a feasibility demonstration prototype quickly.

3.2.1.4 UV Laser. The use of an UV laser can increase the signal per pulse detected by eliminating much of the wasted vertical emissions (see appendix B) and decreasing the effective detection bin size (due to the very short laser pulses). Currently, lasers emitting in the UV spectrum are all relatively large and expensive, making them impractical for field equipment at this time. However, industry is in the process of miniaturizing the laser components and reducing the power requirements, so that UV lasers of practical sizes may be available in the near future.

This will be useful for the Company Radio and the low-data rate LAN Backbone applications, since the short effective bin size should suppress the UV noise sources. With much smaller bin sizes (0.5 μs versus 416 μs), it is hoped that the UV noise sources will have time characteristics of longer duration. Thus, the noise will be spread out over these 832 bins and resemble a DC source. The laser "pulse" in an ON bin would then overwhelm the semiconstant noise.

However, the use of UV lasers may not be as effective for the high data rate LAN Backbone and Wideband Link. A data rate of 2 Mbps limits the bin size to 0.5 μs, which is equivalent to 150 m of path difference. This path difference is too small for practical NLOS mode operations. Thus, while some scattered (near receiver) photons are usable, these high-data-rate links will require LOS mode operation. Since LOS is required for the high-data-rate links to work, the time spreading due to the multipath flux is negligible relative to the LOS photon flux.

3.2.1.4.1 Nd:YAG Laser. A frequency-quadrupled, Nd:YAG laser produces UV light with wavelength of 266 nm. A quadrupled Nd:YAG laser requires only two crystals in addition to the basic Nd:YAG laser, which emits at 1064 nm. This is the simplest solution to obtaining solar-blind UV radiation, but tunability would be difficult.

The UV output wavelength can be Raman shifted to various discrete wavelengths with gas cells or optical fibers. However, the threshold laser energy density (at the needed repetition rate) required to initiate the Raman effect may not be feasible at the present time.

Currently, a quadrupled Nd:YAG laser can satisfy the output requirements of a 2400-bps system within a factor of two, although its size precludes its use in a field experiment. Also, portable, diode-pumped Nd:YAG lasers with about one-tenth of the needed output are now commercially available. Therefore, it is reasonable to conclude that a solid-state laser satisfying the requirements will be available within a few years.

3.2.1.4.2 Ti:Sapphire Laser. A tunable, frequency-tripled, Ti:sapphire laserhead produces UV light with discrete wavelengths ranging from 265 to 280 nm. The laser output can be tuned by rotating a set of birefringent filters (BRF) inside the laser cavity.

The Ti:sapphire laser can be tuned electro-optically (and mechanically) to various wavelengths for multichannel use. The response time can be as fast as 50 ns after a new BRF configuration is set, but setting the configuration mechanically will take more time. A tunable laser capable of emitting at several distinct wavelengths means that only one transmitter would be necessary to produce the multiple links in a multichannel net.

The Ti:sapphire laserhead will require a pumping laser emitting in the green-yellow spectral region. One obvious candidate is the doubled Nd:YAG green laser. Another is the copper vapor laser, emitting in a green line and a yellow line. Finally, a green argon ion laser can be used. The problem will be finding one of these pump lasers with sufficient power.

3.2.1.4.3 Copper Vapor Laser. A copper vapor laser emits at 510 and 578 nm, which can then be doubled within the laser cavity to 255 or 289 nm, respectively. The same power limitation as that of Ti:sapphire laser exists for this laser, but only one laser and a doubling crystal is necessary.

A gas laser is large and cumbersome, with little likelihood of being eventually reduced in size to satisfy operational requirements. Also, it is questionable whether a copper vapor laser can run in CW mode and be modulated sufficiently fast.

3.2.1.4.4 Excimer Lasers. Excimer lasers would be capable of emitting in the UV, but liquid lasers have the same disadvantages as gas lasers in size and weight limitations.

3.2.1.4.5 Laser Power Limitations. A continuous laser, with Q-switching, that provides a pulse energy, E, at a particular repetition rate, f, will have a total output power, P, according to the following relationship:

$$P = E\,f. \tag{1}$$

Note that current UV laser technology limits P to less than 1 W. This should be sufficient for low-data-rate (2400 bps) systems such as the Company Radio and LAN Backbone (at low-data rate).

Appendix B indicates that the Wideband Link at 2 Mbps and 3 km requires a "pulse" energy of 2 μJ, or a laser with UV power output of 4 W. This is equivalent to about 40 W in the green, which is an industrial laser. Such a laser would have major size and safety problems, making it impractical at this time.

Since no pulsed UV laser running at 2 MHz will have the power required, a continuous wave (CW) laser is needed. The CW laser output can be gated with an electro-optic modulator (EOM), which are commercially available at the required rates (although thermal buildup in the modulator may be a problem).

Laser-diode pumping may eventually result in a practical UV laser with the desired characteristics. Although the recent announcement of a blue-green laser diode is encouraging, that technology is not mature enough at this time for practical use. While the requisite (IR) diode arrays exist, the cost (≈$1M) is prohibitive at this time.

3.2.1.4.6 Laser Safety. The advantages of using UV lasers are balanced by safety limitations, detailed in *Exposure to UV Radiation* (Yen et al., 1987b) and updated in appendix C.

3.2.1.5 Beam Optics. By channeling the laser output through some optics (see section 4.1.2), omnidirection operations with one laser can be achieved for the Company Radio. By some kind of mechanical beam channel, multiple directions (one at a time) can be achieved for the LAN Backbone.

The Wideband Link presupposes LOS operations, with the terminals fixed after acquisition. Therefore, there is no need to modify the beam, except to modulate it.

A problem at the antenna farm may arise when it needs to communicate with several CPs at the same time. Unless a timesharing scheme is used optically, this may require several sets of transmitters and receivers at the antenna farm for multiple links.

3.2.1.6 Multichannel. The best alternative to achieve multichannel capability would be a laser tunable to several distinct wavelengths. The transmitter would switch to a set laser wavelength for each terminal it communicates with (see section 3.2.5).

3.2.2 Infrared Light. Infrared (IR) radiation is strongly absorbed by water vapor between wavelengths of 1 and 8 μm (10 to ≥ 100 dB/km, see figure 9). IR lasers exist that can be tuned to one of the water vapor absorption regions, resulting in a very short operations range.

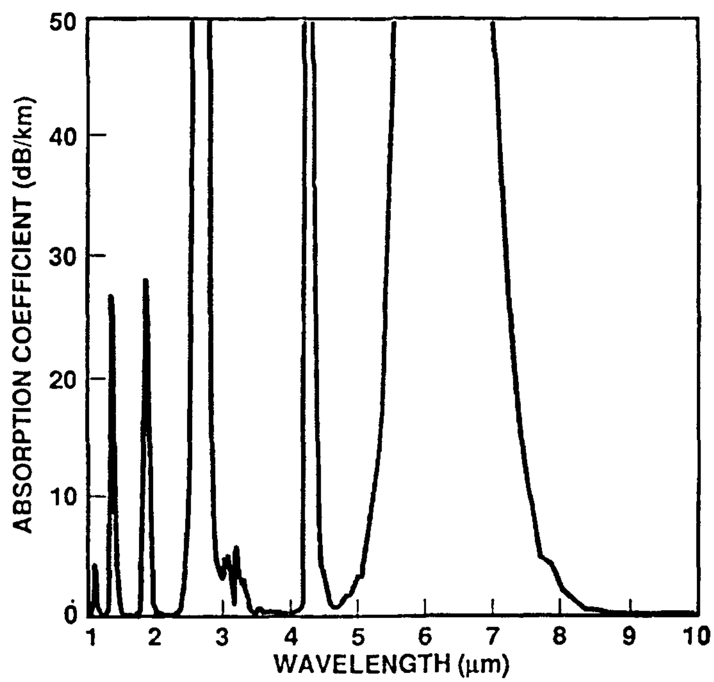

Figure 9. IR absorption by water vapor (Waldman).

3.2.2.1 IR Laser. The absorption coefficient required to reduce the operational range to 0.5–1 km is on the order 5 to 20 dB/km, which means that a possible wavelength region required is, for example, from 1.3 to 1.4 μm. There are solid-state IR lasers that operate in this region, such as Nd:YAG-2 (1.32 μm). These small lasers are available.

3.2.2.2 Attenuation Problems. A possible problem that needs to be addressed is that the absorption coefficient depends on the relative humidity, which is not a constant like oxygen content. In a desert, the daytime humidity can be so low that the IR link range may become so large as to be no longer covert. In a tropical climate, the humidity may limit the range so as to be impractical. Therefore, it will probably be necessary to tune, in power or wavelength, the laser to fit the local (and changing?) humidity conditions.

Similarly, IR rain attenuation may pose a problem in rainy tropical regions.

3.2.2.3 Operational Mode. The IR option also requires that the signal be strong enough to overcome solar and other types of interference, even though the water vapor present should reduce the solar noise at the operations region considerably. The noise will require LOS operations.

While IR laser should not be hard to diffuse without too much loss, the interference may make multiple directions operation impractical.

3.2.2.4 Data Rate. A final problem is that the repetition rate of pulsed IR lasers with the requisite power are slow, on the order of tens of hertz. While diode pumping may resolve this problem, the technology for such a diode array is only developing, with the current cost prohibitive ($1M for an array). This means that an IR laser system has no appreciable advantage over an UV laser system and lacks NLOS capability.

An alternative solution is to gate a CW laser electro-optically. Powerful CW IR lasers with the requisite power output exist and electro-optic modulators at high rates at IR wavelengths are available commercially. This would make the IR laser an attractive option for high-data rate applications, in which NLOS operations is not required.

3.2.3 Millimeter Wave

Millimeter wave (MMW, a form of microwave) or extremely high frequency (EHF) radiation is absorbed very strongly ($\approx$15 dB/km) by the molecular oxygen in the atmosphere at 60 GHz (see figure 10 [Ippolito]). Its range is similar to that of UV links.

Through the use of a bicone antenna (two cones with their tips touching), MMW can be transmitted and received in all azimuthal directions, thereby satisfying omnidirectionality. However, the MMW link is primarily a LOS link, with no obstructions between antennas. An MMW link with an omnidirectional antenna also can exploit multipath propagation modes when obstructions to LOS exist.

The MMW option also requires that the signal be strong enough to overcome the noise from the solar and background sources, although the molecular oxygen and water vapor present should reduce the solar noise considerably.

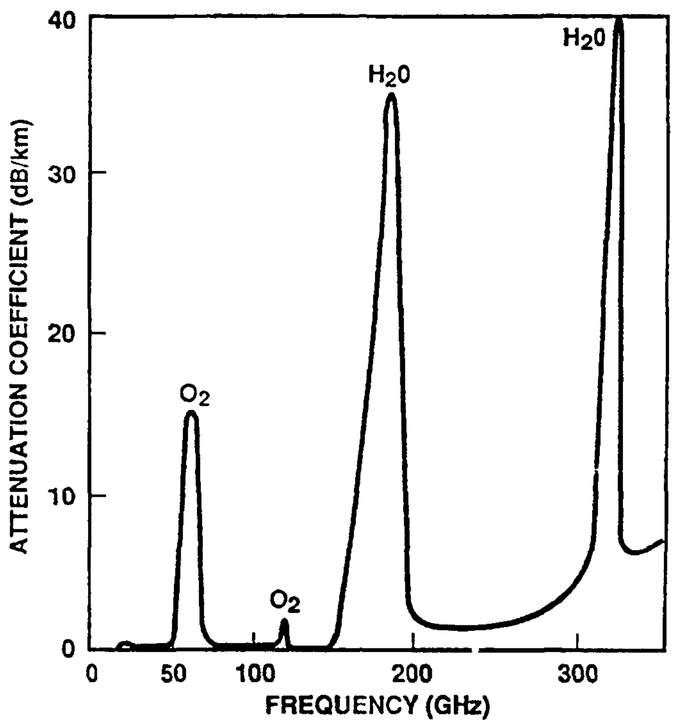

Figure 10. Microwave gaseous attenuation coefficients (Ippolito).

The MMW beam will suffer some loss due to water vapor (humidity). MMW will suffer considerable loss due to passage through rain (about 12 dB/km at moderate rain of 1 in/hr, see figure 11 [Jursa]), although the beam path length is small (see appendix D).

3.2.4 Link Comparison

The three options considered above each has its own advantages and disadvantages. None of them will satisfy all three fundamental requirements of the ISRC links:

(a) limited LPDF range coupled with a reasonable operational range,

(b) NLOS characteristics within the operational range,

(c) and sufficient bandwidth for both low-data-rate links and high-data-rate links.

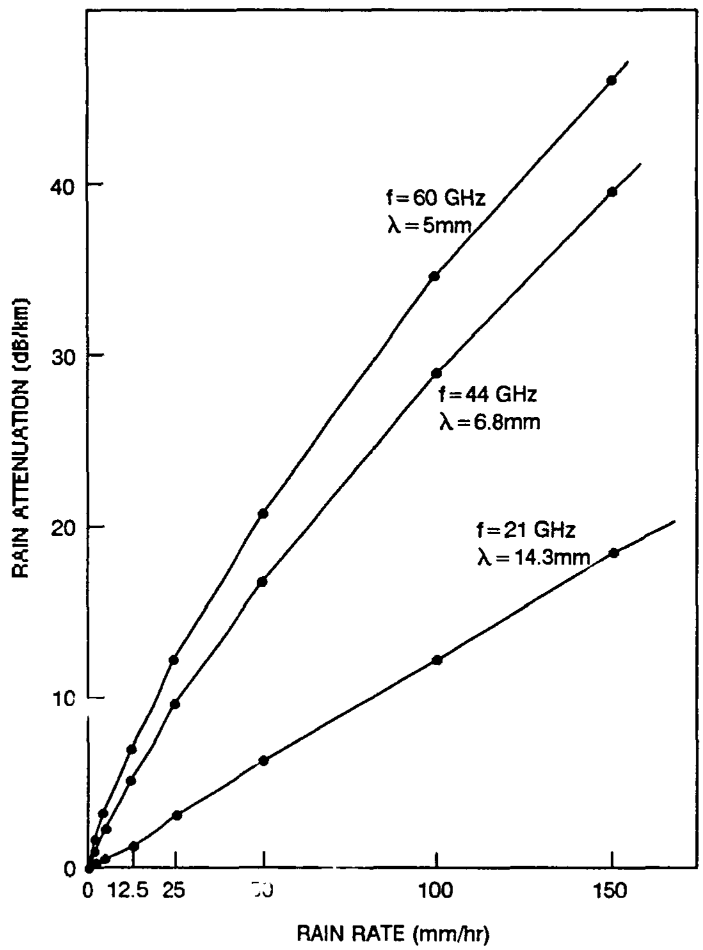

Figure 11. MMW rain attenuation (Jursa).

By carefully selecting the wavelength of the propagation medium, it is possible for all three links to satisfy condition (a). However, the wavelength selection impacts on the other two conditions.

The UV link will satisfy condition (b) by its very nature, while the IR and MMW links will have difficulty with this condition (see figure 12 for comparison of the misalignment allowed).

The MMW link will easily satisfy the high data-rate portion of condition (c) because of its wideband nature. An IR link can be made to satisfy condition (c) with some effort, but the UV link has no foreseeable likelihood to satisfy this condition.

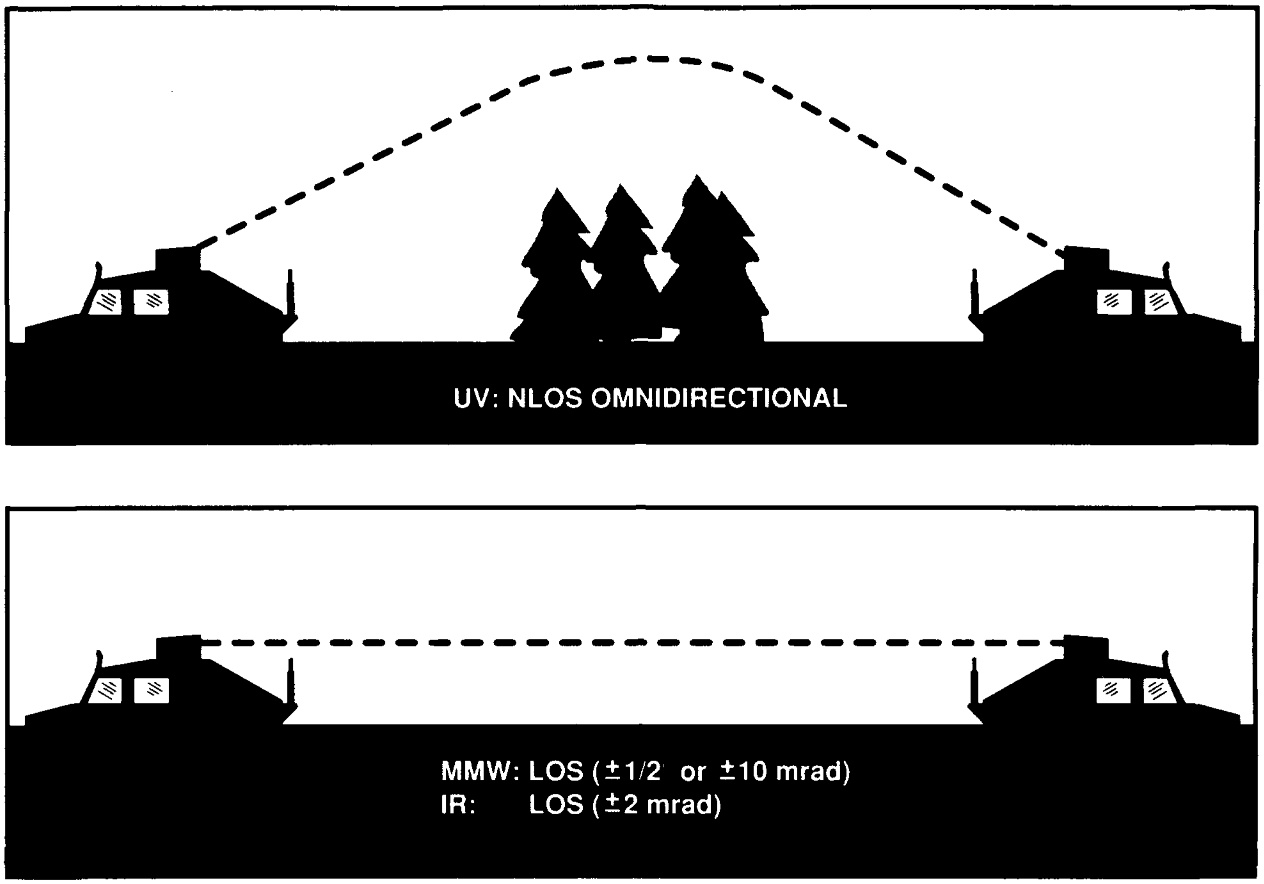

Figure 12. Link comparison.

3.2.5 Multichannel

Simultaneous multiple users require discriminant carriers or some scheme such as time slot assignment, message packets, or collision sensing for multichannel capability. Time assignment or call sign procedures in the early feasibility test units require only one carrier, but they will reduce the data rate assigned to each user.

Discriminant optical carriers will require single-line or narrowband transmitters and discriminating receiver filters. Considerable research and development will be required to achieve multichannel capability with the optical links.

3.2.5.1 UV. Multiple wavelengths for UV light is not easily achieved, since there are few natural UV emitters in that region. Most of the lasers in that region require that they be frequency-upconverted into the UV region. This makes tunability difficult because different wavelengths are difficult to maintain through the upconversion and a difference in the fundamental is much larger than the corresponding difference in the final wavelength.

3.2.5.2 IR. Tuning IR laser at the fundamental wavelength is more practical, but not necessarily easier because the desired wavelength region is relatively small.

3.2.5.3 MMW. Multichannel should not be a problem with the MMW link, since it is a wideband system by definition and has plenty of bandwidth to spare.

3.3 RECOMMENDATIONS

The best technological options for the various ISRC links depend on the specific requirements of each link.

3.3.1 Company Radio

The best options for the Company Radio voice link seem to be omnidirectional UV and MMW that will cover a small area, relieving the need to aim the communications unit.

3.3.1.1 UV Lasers. A tunable UV laser, to take advantage of its single-wavelength tunability and noise suppression characteristics, and the necessary electronics and optics should be developed to satisfy the requirements of the Company Radio.

3.3.1.2 UV Lamps. Directional arc lamps should be usable for the voice link. The use of broadband transmitters will be problematical when multichannel aspects are to be considered. However, the most significant problem is omnidirectionality, and suggestions of rotating or multiple transceiver are probably impractical. Since a rotating transmitter will spread the signal over all azimuthal angles, the lamp output must be increased greatly. Multiple transceivers will increase the hardware cost correspondingly.

3.3.1.3 MMW Links. An MMW antenna and the required baseband electronics should be developed in order to satisfy the requirements of the Company Radio.

The Army Communications and Electronics Command's (CECOM) extremely high frequency (EHF) applique is currently available for testing.

3.3.1.4 IR Links. An omnidirectional IR laser link is not likely based on the available information, so should not be pursued at this time to conserve limited resources.

3.3.2 LAN Backbone, Low-Data Rate

The best options for the low-data rate LAN Backbone link seem to be directional UV that will cover a small area, relieving the need to aim the transceiver very precisely.

3.3.2.1 UV Lasers. A tunable UV laser, to take advantage of its pulsewidth, directionality, single-wavelength tunability, and the necessary electronics and optics should be developed to satisfy the requirements of the LAN Backbone.

3.3.2.2 UV Lamps. Directional arc lamps may be usable for the data links. The use of broadband transmitters will be a problem when multichannel aspects are to be considered. However, their most significant problem is multiple directions, and suggestions of multiple transceiver are probably impractical because of the increased hardware cost. Rotating transceivers may be viable if the acquisition and tracking problems are resolved.

3.3.2.3 MMW Links. An MMW antenna and the required baseband electronics can be developed in order to satisfy the requirements of the LAN Backbone.

The EHF applique would require a considerable amount of modifications to be practical for the LAN Backbone.

3.3.2.4 IR Links. An directional IR laser link is a viable alternative for the LAN Backbone and should be seriously considered.

3.3.3 Wideband Link and LAN Backbone, High-Data Rate

The best options for the Wideband Link and the high-data-rate LAN Backbone link seem to be LOS MMW that will cover a small arc, so that the system must be aimed with some precision.

3.3.3.1 UV Lasers. UV lasers are unlikely to provide the high data rates required, so should not be considered at this time to conserve resources.

3.3.3.2 UV Lamps. UV lamps simply cannot achieve the necessary data rates at the required ranges, so should not be considered.

3.3.3.3 MMW Links. An MMW antenna and the required baseband electronics can be developed to satisfy the requirements of the Wideband Link.

The EHF applique would require a great number of modifications to be practical for the Wideband Link.

3.3.3.4 IR Links. A directional IR laser link is a viable alternative for the LAN Backbone and should be seriously considered.

4.0 SYSTEM DESCRIPTIONS

Several breadboard/brassboard systems based on different technologies (UV laser, UV lamp, MMW, and IR laser) are suggested below for technological feasibility testing. These demonstration systems are not expected to be fully fieldable, but shall satisfy the ISRC test protocols requirements as specified in appendix A.

4.1 UV LASER LINK

The proposed simplex UV laser link shall have a design represented by the block diagram in figure 13.

In the LAN Backbone, the computer terminals send out a digital data stream. In the Company Radio, analog voice from the microphone will be converted by the vocoder card into a digital data stream. The modem converts this data stream into a control data stream, which is then used to trigger the laser pulses. The laser pulses are emitted via an optic device toward the desired azimuthal direction(s).

The UV light photons are scattered in the atmosphere and collected at the receiver. The photons first pass through a filter that blocks radiation outside of the solar-blind region. A UV sensor detects the photons and sends signals to the modem, which integrates these signals to determine where the laser pulse is (that is, what data bits the laser pulse represents). The modem converts the pulse-coded data stream back into a simple data stream for the computer terminals and the vocoder card.

4.1.1 Ti:Sapphire Laserhead

A Ti:sapphire laser (see figure 14) can emit pulses with the following characteristics: pulsewidth of 75 ns, pulse energy of 0.2 mJ, time between pulses of $\leq$150 μs, and wavelength between 265 and 280 nm. For demonstration purposes, the laser shall be powered from AC outlets.

4.1.2 Pump Laser

A Ti:sapphire laser requires pumping by a doubled Nd:YAG laser, a copper vapor laser, or an argon ion laser. It is argued that gas lasers will be too large and expensive for field operations, with little prospect of reductions in the near future. A solid-state laser such as the Nd:YAG has the best prospect of becoming compact and efficient enough to satisfy ISRC requirements. At this time, air-cooled, diode-pumped Nd:YAG lasers have output of about 10 percent of the water-cooled, flashlamp-pumped lasers, but are small enough for breadboard use.

4.1.3 Quadrupled Nd:YAG Laserhead

An alternative method for obtaining UV laser pulses, for testing purposes, is to use a quadrupler crystal after the doubled Nd:YAG pump laser (see figure 15).

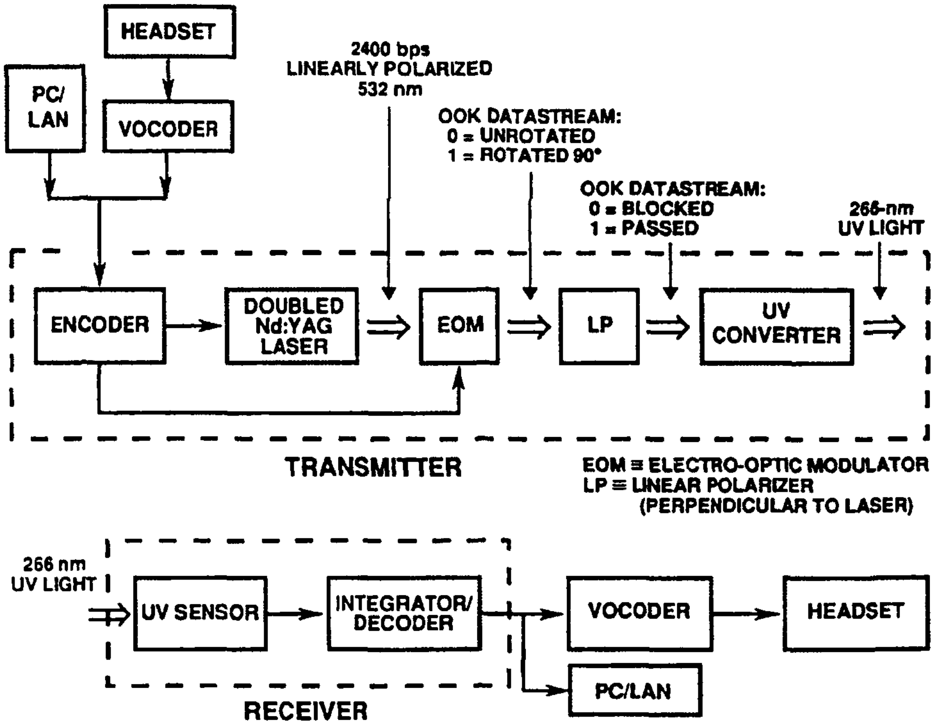

Figure 13. ISRC UV laser link.

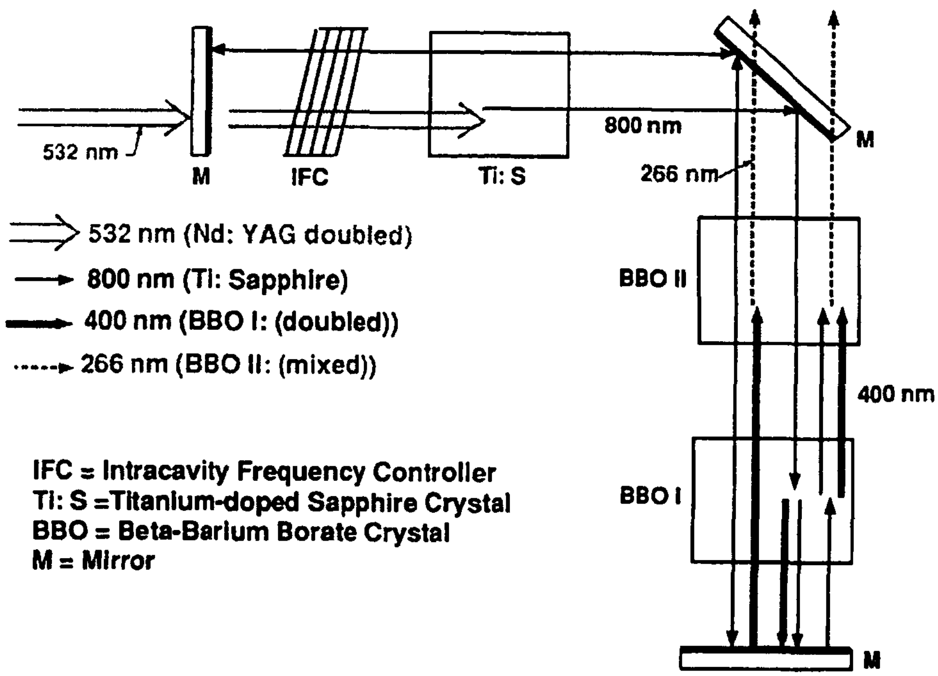

Figure 14. UV converter: Ti:Sapphire tuning element.

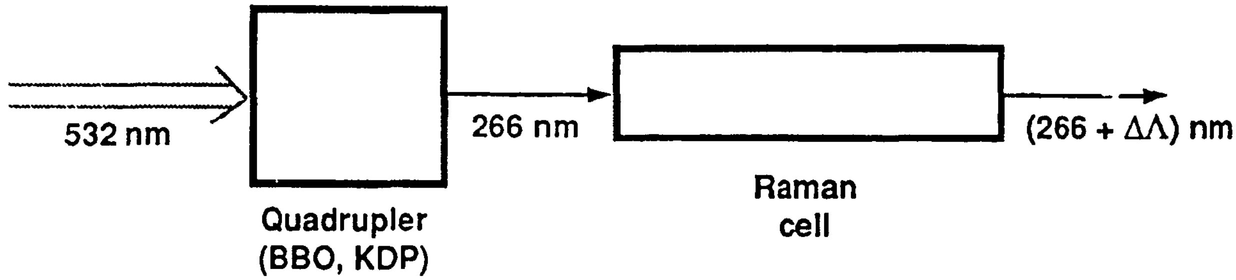

Figure 15. UV converter: Raman cell tuning element.

This method would provide a quick and low risk source of UV laser pulses for electronics and propagation testing, since the output characteristics from the two laserheads should be almost the same. The quadrupled Nd:YAG laserhead would be easier to set up and maintain for testing purposes, while the prototype tunable Ti:sapphire laserhead is expected to be delicate.

4.1.4 Beam Optics

An optical device, such as a UV optical fiber, will be needed to direct the laser beam into the desired regions for each of the links considered here.

The loss within the optical fiber is small since the fiber length is less than 4 m. However, the coupling loss at the fiber input interface is about 4 dB, that is, a loss of about 60 percent. Therefore, assume a fiber loss of 75 percent, or 6 dB.

Angling the optical fiber ends upward, by an angle greater than the beam spread angle at the exit from the optic fiber, should solve the eye safety problem (see appendix C).

4.1.4.1 Omnidirection. A bundle of optical fibers will split and redirect the laser beam in all directions to achieve Company Radio omnidirectionality. By emitting the laser radiation almost horizontally, the system will gain up to a factor of 10 in signal strength (see section B.3.1.1 of appendix B).

The laser beam should be evenly distributed over the fiber bundle to produce a symmetrical spatial signal distribution.

4.1.5 Link Budgets

The expected strong signal near colocated transmitters will require some form of automatic gain control (AGC), to keep from saturating the PMT. The simplest method is to turn off, or mechanically block, the PMT near the laser whenever it is emitting.

While the losses due to environmental variables (such as pollution, fog, and rain) will be considerable, the significant signal margin and the short range should make the Company Radio and the LAN Backbone operational most of the time.

4.1.5.1 Company Radio. Given a Ti:sapphire laser as specified and an optical fiber bundle device as described above, the number of received UV photons per pulse will be in the tens (see section B.3.2.1 of appendix B for details). This large signal may allow the use of less expensive PMTs and interference filters, but not photodiodes.

The intercept range of the laser link is about 1.5 km and the detection range is about 2.5 km (see section B.4 of appendix B).

4.1.5.2 LAN Backbone. Given a Ti:sapphire laser as specified and an optical fiber channel, the number of received UV photons per pulse will be in the hundreds (see section B.3.2.2 of appendix B for details). This large signal may allow the use of less expensive PMTs and interference filters, but not photodiodes.

The intercept range of the laser link is about 2.5 km and the detection range is about 3.5 km (see section B.4 of appendix B).

4.1.5.3 Wideband Link. Given a Ti:sapphire laser as specified and an optical fiber channel, the number of received UV photons per pulse will be few (see section B.3.2.3 of appendix B for details). This small signal is insufficient for a practical UV link.

The intercept range of the laser link is about 3.5 km and the detection range is about 4.5 km (see section B.4 of appendix B).

4.1.6 Link Modulation

For good quality voice (word and voice recognition) using commercial vocoders, a data rate of 2400 bps will be required. Similarly, a reasonable data link connected to a modem would generally need to be at least 2400 bps.

This means the laser will have be capable of emitting about 2400 pulses per second using the pulse-coded modulation scheme.

4.1.6.1 8-ary Modulation. By the use of an 8-ary modulation scheme, the laser will only need to emit about 924 pulses per second. This will increase by almost threefold the laser lifetime, which is usually measured by the cumulated number of pulses emitted. However, this is balanced by the fact that the laser must be capable of operating at repetition rates of greater than 7 kHz, because the minimum time between pulses is 152 μs.

This repetition rate is higher than the specified capability of the proposed Ti:sapphire laserhead.

4.1.6.2 Time Spreading. The time spreading of the laser pulse over 0.5 to 1 km is less than 5 μs (see section B.1.3 of appendix B), so that there is little likelihood of pulse tail confusion.

The small time spreading means that less signal photons need to be detected at the receiver to ensure that a pulse had been sent (see appendix E for details). Bins of 5 μs are equivalent to an average noise level of 0.012 pulse per bin, so that only about 5 pulse photons will generate a 99 percent confidence that a pulse will be detected (see figure E-1). Even if the pulse is detected by two bins, only about 10 photons are necessary. Thus, 10 photons per pulse at the receiver is the minimum required for the link budget.

4.2 NRaD MMW LINK

In 1982, NOSC developed a small 60-GHz communicator for short-range communications. It was an omnidirectional, LOS, 8-channel link with a range of only about 90 m. NRaD proposes to improve upon this basic design and build a MMW link that will satisfy the Company Radio requirements. The transceiver will be a stand-alone unit not dependent on other radio equipment, with the intermediate frequency (IF) radiation shielded for covertness.

4.2.1 MMW Transceiver

NCCOSC proposes to improve on the NOSC 60-GHz bicone antenna design for use in the MMW link.

4.2.1.1 Mixer/Oscillator. The transceiver package that transmits and receives the EHF signal will directly convert a (voice) data stream to frequency-shift (FSK) EHF. The improved communicator will use narrowband (40-MHz bandwidth) IF amplifiers instead of the broadband (400 MHz) stages previously used. This is possible because of a NOSC-developed frequency stabilization technique, which forces the internal Gunn device to oscillate at a frequency determined by an external discriminator (see figure 16).

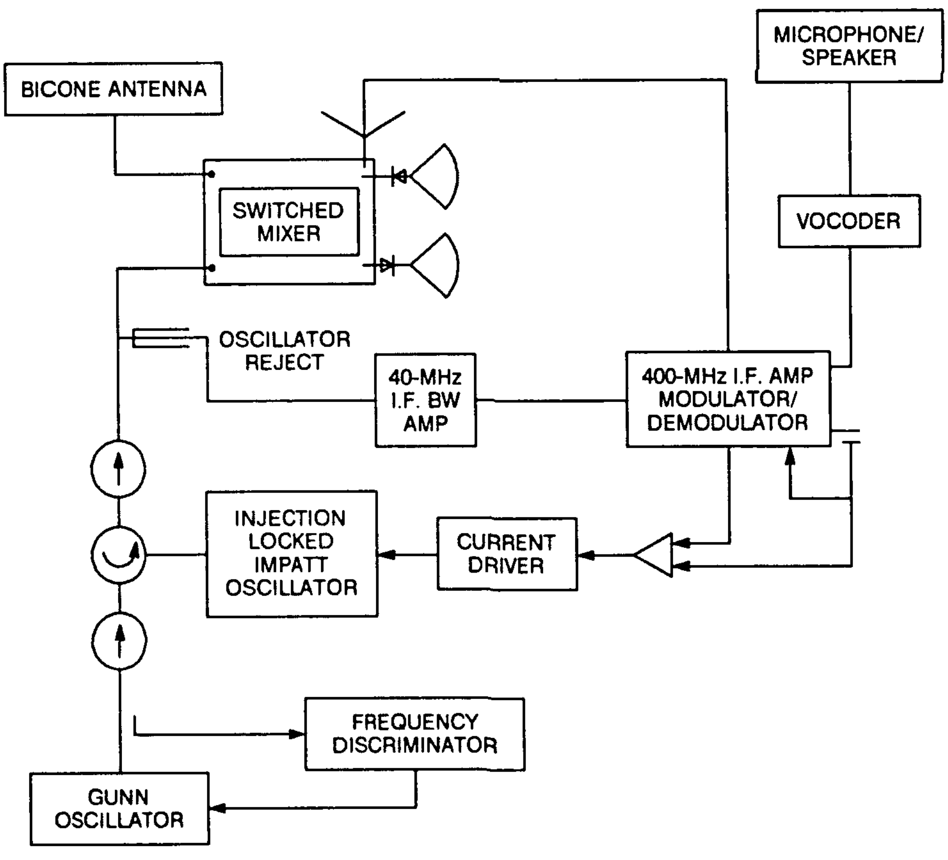

Figure 16. NRaD MMW link block diagram.

4.2.1.2 Noise. The increased stabilization allows a decrease by a factor of 10 in the bandwidth. Therefore, the range increases by the square root of 10 to about 280 m.

4.2.1.3 Power. The improved NRaD MMW transceiver design increases the output power by a factor of 10 with the use the injection-locked IMPATT. Therefore, the operational range again increases by the square root of 10 to about 900 m.

This range is greater than the 0.5 km desired for the Company Radio, but will be valuable as a rain margin. If the MMW link is adapted for the low-data-rate LAN Backbone, this range is not quite enough.

4.2.2 Baseband

Because of the simplicity of the NRaD MMW transceiver design, the only baseband equipment needed will be a vocoder card to convert voice into a digital data stream and back. The vocoder card can be designed into the transceiver unit to reduce the pieces of equipment being demonstrated.

4.2.3 Link Budgets

Given the MMW link as specified above, the Company Radio will then operate with a clear air link margin of +24.4 dB (see section D.2.5 of appendix D). However, the low-data-rate LAN Backbone adaption will have a link margin of +10.9 dB.

Under some weather and obstruction conditions, the losses to the NRaD MMW link will be greater than the above link margins, and the link will not be operational (see table D-1 in appendix D).

The maximum intercept range of the ISRC MMW link is less than 3 km and the maximum detection range is less than 4 km (see section D.5 of appendix D).

4.3 UV LAMP LINK

At least two companies (SPARTA LSL of San Diego and GTE of Mountain View, California) have developed short-range communications links using UV lamp technology. SPARTA LSL had fabricated a 2400-bps directional voice link. GTE had fabricated a 2400-bps data link. Such a lamp link will have the configuration shown in figure 17, which will allow either the Company Radio (voice) or the low-data-rate LAN Backbone (data) to be connected to the link.

While it is possible to contract with one of the above companies to fabricate a duplex, UV, voice (or data) link for quick demonstration purposes, it must be noted here that these UV links, as presently configured, do not satisfy the Company Radio (or low-data-rate LAN Backbone) requirements.

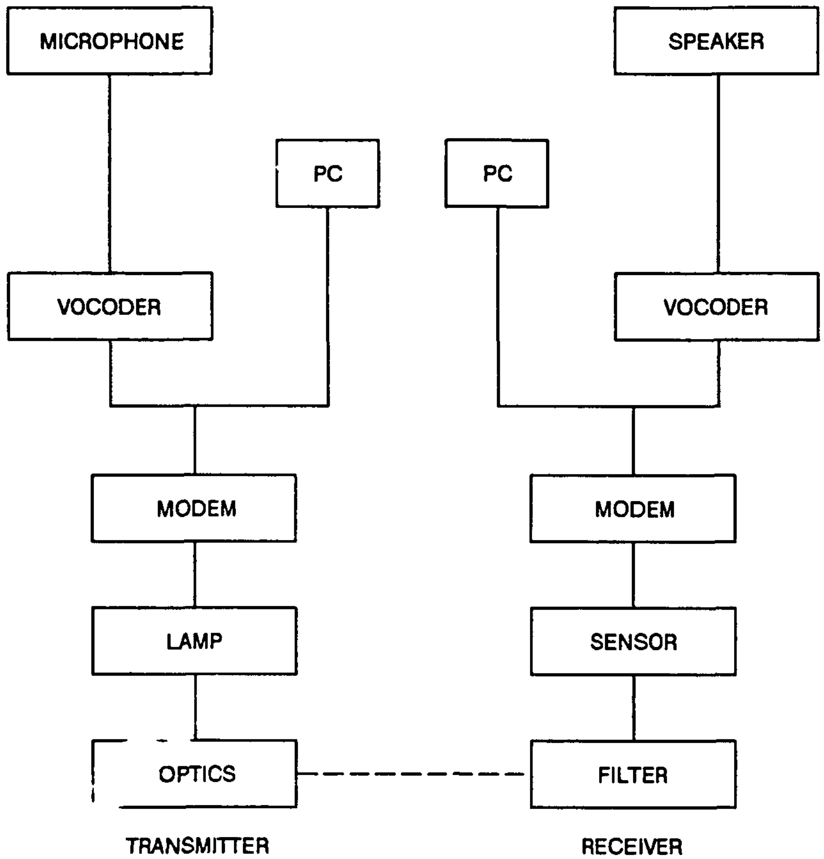

Figure 17. UV lamp link block diagram.

The arc lamps used are compact, but they are broadband emitters, thus making them difficult to use for multichannel applications. At this time, the radiation from the lamps is directed using reflecting surfaces, and much of the energy is lost unnecessarily. There are also some doubts as to the output power and the IR and visible signatures of the arc lamps.

4.4 COMMERCIAL EHF LINK

4.4.1 EHF Applique

A commercial EHF attachment to an ultrahigh frequency/very high frequency (UHF/VHF) radio is available (Diederichs, Himes, & Christianson, 1989). Its use is shown in the block diagram of figure 18. This Hughes EHF Applique operates at 54 GHz (5.6 mm) in frequency-modulated (FM) mode for a maximum ideal operational range of about 4 km and detection range of about 8 km (see appendix F for specifications).

The EHF applique uses a dual conversion heterodyne scheme to convert the 54 GHz to UHF/VHF. The MMW section consists of an injection-locked source at 54 GHz, a mixer that operates as both up-converter and down-converter, an IMPATT

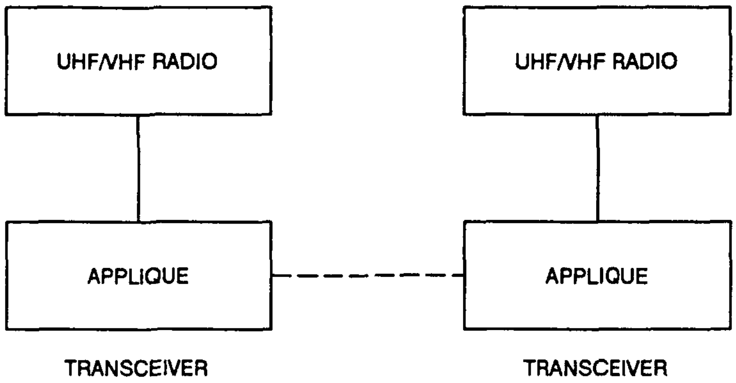

Figure 18. Commercial EHF link block diagram.

amplifier with latching circulators for transmit and receive bypass, and a 2-inch bicone antenna on a 1-foot mast. The first IF at 1.7 GHz is converted to the UHF/VHF radio-operating range using a source locked to the same 10 MHz as the 54-GHz source.

The applique operates push-to-talk and interfaces directly with existing UHF/VHF radios, including the power supply. The only manual control is a switch on the applique that changes between UHF/VHF radio or EHF mode. The applique has been designed to operate at 100-W input power if the power of the UHF/VHF radio has failed. Hughes also developed an antenna mount for the applique's bicone antenna that integrates the bicone with existing VHF whip antennas.

The appliques have been used to evaluate the MMW link in an outdoor environment. Hughes has tested link operation when experiencing foliage loss, evaluated beyond LOS performance, and characterized the impact of applique mobility. With the current 1-watt output, reliable communication was maintained for distances on the order of 2 to 2.5 km. The EHF appliques have also been evaluated in sea tests aboard destroyers during submarine sweeps on the West Coast.

Hughes has spent approximately $2.6M in its development effort of the EHF applique. Five units have been built: four transmit/receive and one receive only. The applique was designed to fit on a standard VRC radio vehicle mount. Its packaging was not optimized and Hughes feels that the overall size can be reduced.

4.4.2 Frequency Switching

One possible use for the EHF applique is to modify it so that it can transmit in one of two frequencies, 60 and 55 GHz. Use 60 GHz when the environmental conditions are good (no rain) and molecular oxygen is the main attenuator. Use 55 GHz during rain, since the greater range of 55 GHz will allow a greater rain margin.

4.4.3 CECOM Efforts

The Army's Communications and Electronics Command (CECOM) is funding the Hughes EHF Applique in FY 92, and expects prototype delivery at the end of FY 92.

The ISRC project expects to be informed of the CECOM test results for those units. Also, the ISRC developers may request a temporary loan of the CECOM units for independent testing with respect to ISRC requirements.

CECOM is also funding in FY 92 the development of a wireless command post. The ISRC project also expects to share in the results of that effort and incorporate that information in the FY 92 project report.

4.5 TESTING

More detailed link requirements must be specified, including some of the operational environments. Given these requirements, the proposed links should be tested to see whether they conform to the requirements. These requirements are stated in appendix A.

4.5.1 BER Testing

An important piece of information regarding the link is the expected bit-error rate (BER) of the link. The BER would affect the performance of the link, whichever of the ISRC links it is. Although error correction theoretically will eliminate the errors in a digital link, a high-BER link with more errors will require more time to correct errors. Therefore, while the data rate is unchanged, the actual throughput is slowed due to the increased overhead.

Figure 19 shows the generic block diagram for a link BER test. In the case of the UV laser link, the transmitter will be the laser output and the receiver will be the UV sensors. By taking data at bin sizes on the order of µs, the advantages of very short (100 ns) laser pulses can be verified. Also, this would allow a more detailed study of noise sources than previously performed.

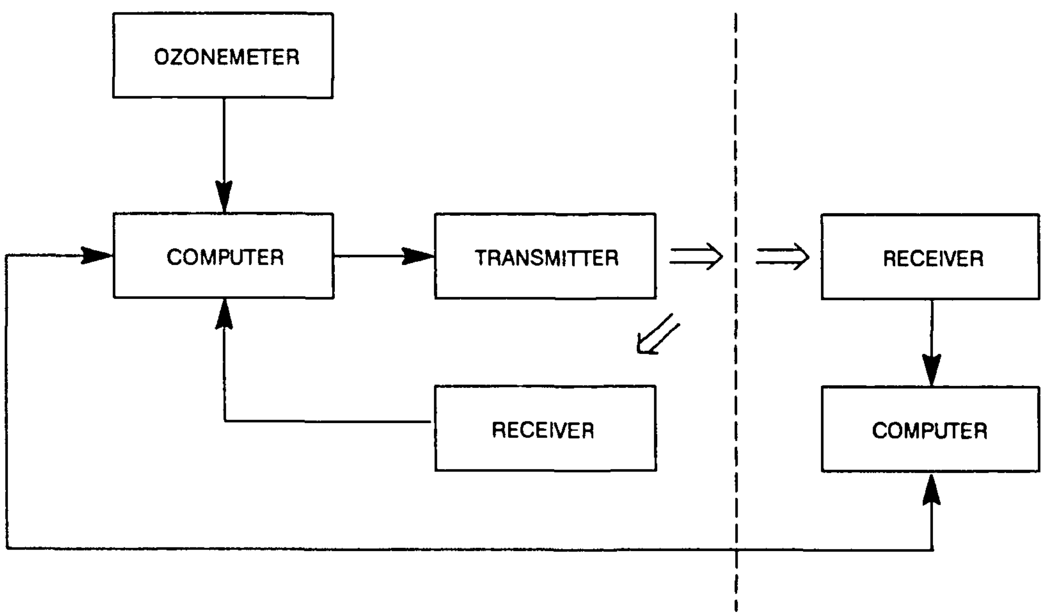

Figure 19. ISRC Company Radio BER test.

4.5.2 Environment

The effects of the local environment (noise sources both natural and man-made) on each proposed link (see sections B.3.5 and D.4) should be tested with the actual equipment to confirm the theoretical calculations. If resources are available and circumstances allow, test the ISRC link in as many likely operational environments as possible.

4.5.2.1 Welding Noise. In view of the comments above, introduce welding noise into the experiment represented by figure 19 and observe the effects on link viability. Study the welding noise characteristics and verify whether the assumption that welding noise will average out over the smaller time periods. This will determine whether the theory, stated in section 3.2.1.4, regarding noise suppression of laser pulses is realistic.

4.5.3 Voice Demonstration

A voice demonstration, as shown in figure 20, satisfies only the Company Radio requirements. However, it will be useful in determining empirically how well the link performs without collecting a huge amount of data as in the BER testing. While this is not a rigorous test, a hands-on demonstration will generate more confidence than megabytes of data.

Note that this demonstration setup can also verify the diagnostic rhyme test (DRT) rating of the voice digitizer boards.

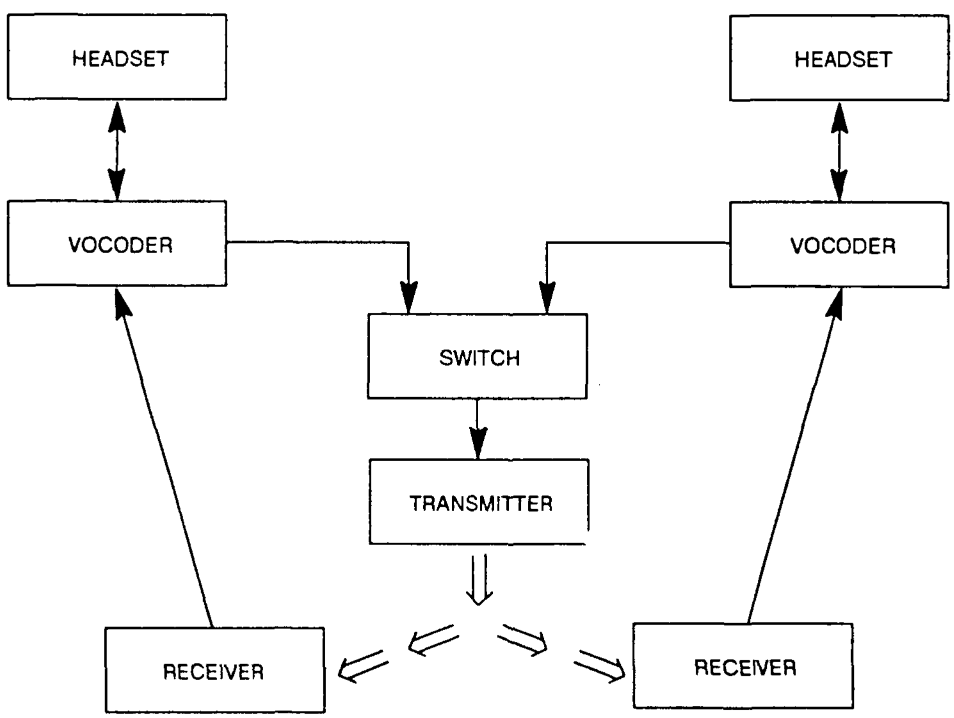

Figure 20. ISRC Company Radio voice demonstration.

4.5.4 Detectability

Interceptibility for each link can be measured by moving the receiver to different locations to check the received signal.

Detectability testing for the UV laser link can be performed by moving the detector away from the transmitter until the signal reaches noise level.

Detectability testing for the NCCOSC MMW link will require a directional antenna. However, indirect measurements can be made with the bicone antenna and extrapolate to a typical directional antenna.

4.5.5 Safety

Comprehensive safety studies must be made for each technology and confirmed with actual measurements of the radiation intensity, with respect to distance and angle (see appendix C for a safety overview for UV links).

5.0 SYSTEMS DEVELOPMENT STRATEGY

5.1 UV LASER LINK

5.1.1 Development Efforts

5.1.1.1 Concept Definition. In FY 91 and FY 92 develop a simplex demonstration unit.

Upon its successful completion, develop duplex demonstration link in FY 93.

5.1.1.2 Systems Demonstration. Breadboard demonstration can begin in the third quarter of FY 93.

5.1.2 Deliverables

Simplex laser link and test report at end of FY 92.

Duplex laser link and test report at end of FY 93.

5.1.3 Milestones

Development test plan	1st Qtr FY 92
Simplex UV laser data link	3rd Qtr FY 92
Preliminary test report	4th Qtr FY 92
Duplex UV laser data link	3rd Qtr FY 93
Development test report	4th Qtr FY 93

The time required to complete and test the UV laser link is FY 91 through FY 93 due to the long lead time necessary for parts procurement and contracting (up to 6–9 months).

Note that the above time period includes a second laser for a duplex demonstration link in FY 93.

Note also that UV Communication sensors are available for use, but they are too large and expensive for production unit. Efforts to develop a cheaper sensor, as well as the transmitter optics, are to be performed in FY 93, if funding is available.

5.2 NRaD MMW LINK

5.2.1 Development Efforts

5.2.1.1 Concept Definition. In FY 93 develop a simplex demonstration unit.

In FY 94 develop a duplex demonstration unit.

5.2.1.2 Systems Demonstration. Breadboard demonstration can begin in the fourth quarter of FY 93.

5.2.2 Deliverables

Simplex MMW link and test report at end of FY 93.

Duplex MMW link and test report at end of FY 94.

5.2.3 Milestones

Development test plan	1st Qtr FY 93
Simplex MMW data link	3rd Qtr FY 93
Duplex MMW data link	2nd Qtr FY 94
Development test report	3rd Qtr FY 94

The time required to complete and test the NRaD MMW duplex link is about 1.5 years after funding begins because of the long lead time required for parts procurement (up to 6 months).

5.3 UV LAMP LINK

Two companies (SPARTA LSL and GTE) have developed short-range communications links using UV lamp technology. They have fabricated simplex UV links: SPARTA LSL had a 2400-bps voice link and GTE had a 2400-bps data link. Therefore, it is possible to contract with one of them to fabricate a duplex data link for a quick demonstration.

It should be noted here that these UV links, as presently configured, do not satisfy the LAN Backbone requirements.

5.3.1 Development Efforts

5.3.1.1 Concept Definition. In FY 92 and 93 develop a simplex data link for the LAN Backbone.

In FY 93 and 94 develop a duplex and/or high-data-rate link for the LAN Backbone.

5.3.1.2 Systems Demonstration. Breadboard demonstration of a UV lamp system can begin in late FY 93.

5.3.2 Deliverables

A simplex, directional, data link that can operate at 1 km, but not detectable at 4 km.

5.3.3 Milestones

A demonstration unit is expected in late FY 93.

5.4 COMMERCIAL EHF LINK

A 54-GHz transceiver has been developed by Hughes Aircraft Company, Ground Systems Group using commercially available components. A procurement had been initiated by the CECOM during FY 92 for four units with antennas.

5.4.1 Development Efforts

5.4.1.1 Concept Definition. In FY 92 develop test plan based on Company Radio requirements.

5.4.1.2 Systems Development. Advanced development can begin in FY 93.

5.4.2 Deliverables

Demonstration of a duplex, omnidirectional, voice link with a range of 0.5 km and a maximum detection range of 4 km (Hughes' EHF Applique). Recommendation for further effort based on the EHF Applique performance.

5.4.3 Milestones

Hughes is expected to deliver to CECOM four EHF applique units at the end of FY 92.

Testing of the EHF applique with respect to ISRC requirements can commence in FY 93.

5.5 IR LASER LINK

An infrared (IR) laser system should be developed that can satisfy the high-data-rate ISRC requirements.

5.5.1 Development Efforts

5.5.1.1 Concept Definition. In FY 92 develop design based on Wideband Link requirements.

In FY 93 develop a simplex demonstration unit.

In FY 94 develop a duplex demonstration unit.

5.5.1.2 Systems Development

Advanced development can begin in FY 94.

5.5.2 Dcliverables

A high-data rate, simplex, IR laser link with test report at the end FY 93.

A high-data rate, duplex, IR laser link with test report at the end FY 94.

5.5.3 Milestones

Design of a high-data rate, simplex, IR laser link with a range of 3 km and maximum detection range of 5 km at the end of FY 92.

Demonstration of a high-data rate, simplex, IR laser link with a range of 3 km and a maximum detection range of 5 km at the end of FY 93.

Demonstration of a high-data rate, duplex, IR laser link with a range of 3 km and a maximum detection range of 5 km at the end of FY 94.

5.6 SBIR

The Small Business Innovation Research (SBIR) program is used to solicit proposals from small businesses to develop systems that can satisfy the ISRC requirements.

5.6.1 Development Efforts

5.6.1.1 Concept Definition. In FY 92 develop a test plan based on, Company Radio and LAN Backbone requirements.

In FY 93 develop a demonstration unit.

5.6.1.2 Systems Development. Advanced development can begin in FY 94.

5.6.2 Deliverables

Design of a simplex link with a range of 1 km and a maximum detection range of 4 km at the end of Phase I.

Demonstration of a simplex link with a range of 1 km and a maximum detection range of 4 km at the end of Phase II.

5.6.3 Milestones

Phase I SBIR contract is expected to be awarded in the second quarter of FY 92.

Phase I of the SBIR contract is expected to be completed at the end of FY 92.

Phase II of the SBIR contract is expected to be completed at the end of FY 93.

5.7 BAA

The broad agency announcement (BAA) vehicle is used to solicit proposals from industry to develop systems that can satisfy the ISRC requirements.

5.7.1 Development Efforts

5.7.1.1 Concept Definition. In FY 92 develop a test plan based on LAN Backbone requirements.

In FY 93 develop a demonstration unit.

5.7.1.2 Systems Development. Advanced development can begin in FY 94.

5.7.2 Deliverables

Design of a simplex link with a range of 1 km and a maximum detection range of 4 km at the end of phase I.

Demonstration of a simplex link with a range of 1 km and a maximum detection range of 4 km at the end of phase II.

5.7.3 Milestones

Phase I BAA contract is expected to be awarded in the second quarter of FY 92.

Phase I of the BAA contract is expected to be completed at the end of FY 92.

Phase II of the BAA contract is expected to be completed at the end of FY 93.

5.8 CONSOLIDATED MILESTONES

The milestones specified above for the various aspects of the ISRC project are consolidated into figure 21.

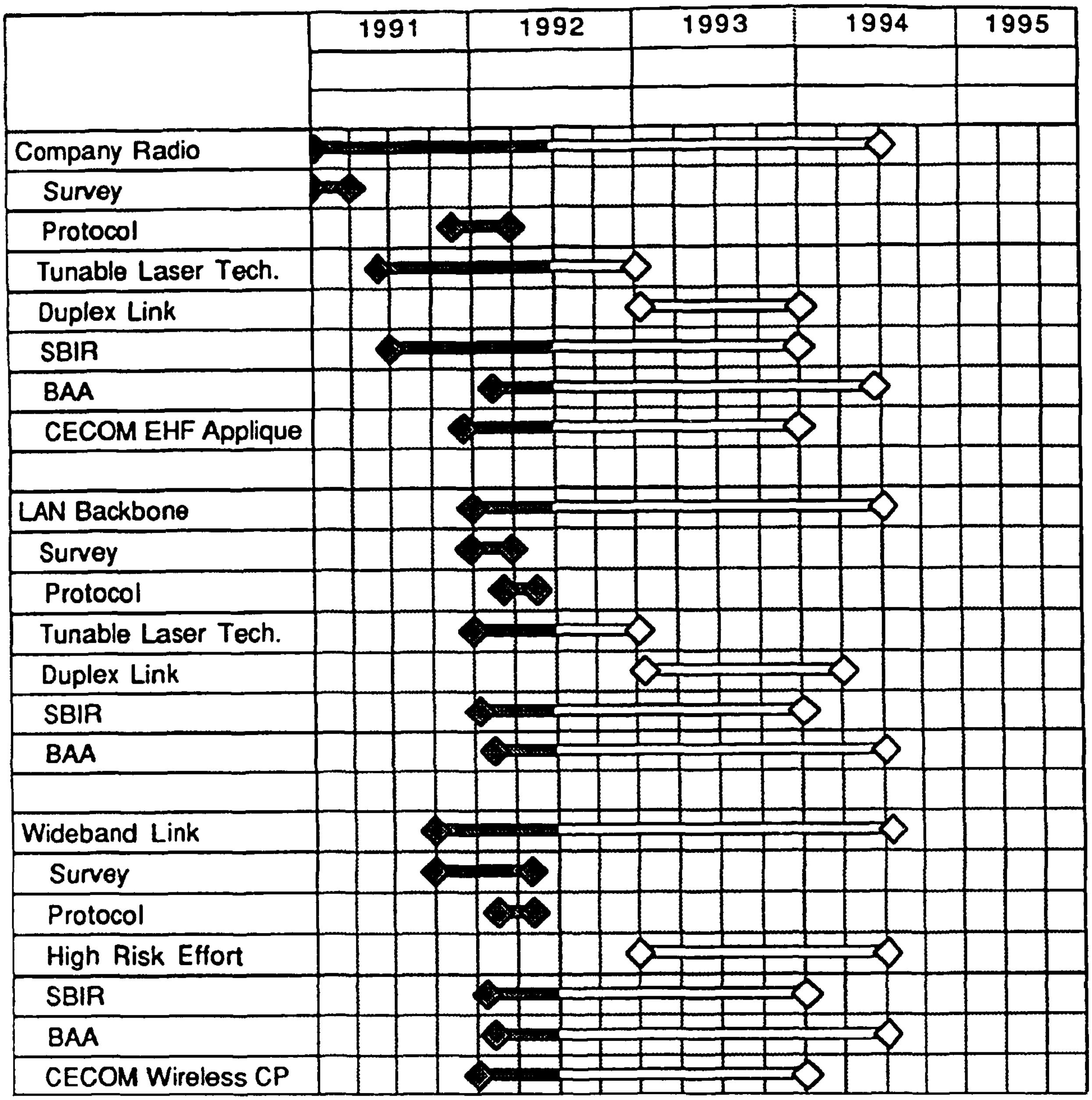

Figure 21. ISRC consolidated milestones.

6.0 MANAGEMENT PLAN

6.1 PROGRAM MANAGER

The Director, Amphibious Warfare Technology Directorate (Code AW), Marine Corps Systems Command (MCSC) is responsible for the Technology Base Exploratory Development (6.2) within the Marine Corps.

The Director is responsible for management, coordination, direction, review, and approval of the development effort. The Director shall provide the overall project direction and guidance to the Development Activity (DA).

6.2 DEVELOPMENT ACTIVITY

Naval Command, Control and Ocean Surveillance Center, RDT&E Division (NRaD) Code 843 has been designated DA for the ISRC development task and shall provide the necessary technical and managerial expertise for successful project execution to meet the ISRC 6.2 Exploratory Development requirements.

Project direction and management support will be provided by the NRaD Marine Corps Liaison Office (Code 033).

Technical support for the project will be provided by NRaD Microwave/MMW Branch (Code 753, MMW link fabrication), Communications Systems Integration Branch (Code 842, systems engineering), and Electro-optic Devices Branch (Code 843, UV laser fabrication).

7.0 COMPARATIVE TESTING

NRaD expects to conduct comparative testing of the various alternative systems developed for the ISRC project (from NRaD in-house effort, SBIR contracts, BAA contracts, and CECOM efforts). The tested systems need to satisfy the requirements specified in appendix A of this document.

The requirements of appendix A are general in scope, so that refinements to these requirements will be included in upgraded versions of appendix A in future publications. Also, the specifics of the required testing will be quantified and incorporated as more information regarding the links become available.

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* NRaD Technical Notes (TNs) are working documents and do not represent an official policy statement of the Naval Command, Control and Ocean Surveillance Center, RDT&E Division. For further information, contact the author.

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9.0 GLOSSARY

AC	alternating current
ACAT	acquisition review category
AGC	automatic gain control
BAA	broad agency announcement
BER	bit-error rate
bps	bits per second
BRF	birefringent filters
Broadband	a broad spectrum of wavelengths
CAINS	Carrier Aircraft Inertial Navigation System
CECOM	USA Communications and Electronics Command
Comm	communications
CP	command post
CW	continuous wave laser
DA	development activity
dB	decibel
dBm	decibel referred to 1 milliwatt
DF	direction find
Directional	direction is within ± 5 deg of the imaginary line between terminals
DRT	diagnostics rhyme test
Duplex	two-way channel
EHF	extremely high frequency, see MMW
EIRP	effective isotropic radiated power
EOM	electro-optic modulator (Pockel cell)
FM	frequency modulated
FSK	frequency-shift keying
FOV	field-of-view
GHz	Gigahertz
hr	hour
IF	intermediate frequency
IR	infrared light, $\lambda \geq 700$ nm
ISRC	Intentionally Short-Range Communications
IMPATT	an oscillating diode
kHz	kilohertz
km	kilometer
LAN	local area network

LOS	line-of-sight, direction within ±1 deg of the imaginary line between terminals
LPDF	low probability of direction finding
LPI	low probability of intercept
m	meter
Mbps	megabits per second
MCSC	Marine Corps Systems Command, Quantico, Virginia
MHz	megahertz
MMW	millimeter wave, with 1 mm $\leq \lambda \leq$ 10 mm, or 30 GHz $\leq \nu \leq$ 300 GHz
μJ	microjoule
μm	micrometer
mJ	millijoule
mrad	milliradian
Multichannel	several communications channel
NCCOSC	Naval Command, Control and Ocean Surveillance Center, San Diego, California
Nd:YAG	neodymium-doped yttrium aluminum garnet crystal
NLOS	non-line-of-sight, or no LOS between the transmitter and the receiver
nm	nanometer
NOSC	Naval Ocean Systems Center, San Diego, California
ns	nanosecond
NRaD	NCCOSC Research, Development, Test and Evaluation (RDT&E) Division (formerly Naval Ocean Systems Center), San Diego, California
Omnidirectional	the signal is sent in all directions azimuthally
ppb	parts per billion
PMT	photomultiplier tube
RF	radio frequency
SBIR	small business innovation research
Semidirectional	the signal is sent into an azimuthal quadrant (±45 deg)
Simplex	one-way channel
SLOS	strictly line-of-sight, direction within ±0.01 deg of imaginary line between terminals
S/N	signal-to-noise (ratio)
Ti:sapphire	titanium-doped sapphire crystal
USMC	United States Marine Corps

UHF	ultrahigh frequency
USN	United States Navy
UV	ultraviolet light, 200 nm $\leq \lambda \leq$ 400 nm
VHF	very high frequency
W	watts
WAN	wide-area networks
Wideband	a wide range of data rates

APPENDIX A—ISRC TEST PROTOCOLS

CONTENTS

FIGURE

A.1 INTRODUCTION

This appendix is written to provide a single set of test protocols, or requirements, that ISRC links will have to satisfy. This appendix will be refined in future publications.

A.2 LINK CHARACTERISTICS

The ISRC link characteristics (such as LPDF, NLOS, and BER) apply to all the ISRC links, although the requirements for these parameters are link-specific.

A.2.1 LPDF

Low probability of direction finding (LPDF) is defined here to mean that the enemy has a low likelihood to detect our transmissions and direction find on them. A system that cannot be detected obviously cannot be intercepted, so the system is inherently low probability of intercept (LPI).

An LPDF link with an operating range of X km must have a detection range of less than X + Y km.

The operational ranges of the ISRC links vary from 0.5 km to 5 km ($0.5 \text{ km} \leq X \leq 5 \text{ km}$). In general, an ISRC link must have a detection range of less than 5–7 km ($X \leq X + Y \leq 7 \text{ km}$), preferably less.

A.2.2 NLOS

The non-line-of-sight (NLOS) characteristic is highly desirable for tactical communications systems, because tactical operations tend to involve situations where there are obstructions to line-of-sight.

While NLOS strictly means there is no single unobstructed line between the transmitter and the receiver, a partial requirement is that the link is viable when there is a misalignment of at least a minimum angle, such as 5 deg.

A.2.3 Temperature

ISRC links must operate in temperatures ranging from 0 to 50 deg C.

A.3 LOW-DATA-RATE LINKS

In general, the Company Radio and the low-data-rate LAN Backbone need to satisfy the same general requirements, because of the similarities of data rate and operational configurations. There are some differences, such as the range, data format, and operational methods.

A.3.1 Company Radio

The Company Radio is characterized by very short-range ($\leq$0.5 km), omnidirectionality, low-data-rate, and mobility (see section 3.1.1).

The major distinguishing feature of the Company Radio is that this is a voice link, which will then tolerate a much larger bit error rate (BER). BER for a reasonable voice system is $\leq 10^{-2}$.

An adequate digital voice system would need at least 2400-bps link throughput. The diagnostic rhyme test (DRT) rating for this voice link should be $\geq$0.90 for good quality voice.

The Company Radio needs to operate in an omnidirectional mode. This means that it is not necessary for the operator to orient the system to communicate, since the positions of other terminals may not be known. However, some aiming to improve link connection would be a useful additional asset.

A.3.2 LAN Backbone

The low-data-rate LAN Backbone is a short-range ($\leq$1.0 km), semidirectional, transportable, data link (see section 3.1.2).

Until a specific LAN operating system (such as MTS) is defined for the USMC, the Banyan VINES LAN will be used to operate the LAN Backbone. The link will be a 2400-bps link connecting a server computer to a terminal computer.

The BER requirement for this data is $\leq 10^{-4}$, which is neither noisy nor very clean.

The low-data-rate LAN Backbone needs to operate in a directional mode in several different directions, although one at a time. This means that it is not necessary for the operator to orient the system very precisely to communicate, such that the link can sustain an angular misalignment of at least 5 deg. However, more precise aiming to improve link connection would be an additional asset.

A.4 HIGH-DATA-RATE LINKS

In general, the Wideband Link and the high-data-rate LAN (or WAN) Backbone need to satisfy the same general requirements, because of the similarities of data rate and operational configurations. Differences exist such as the range, data format, and operational methods.

Since these links are expected to be stationary when in operation and the positions of other terminals should be known, they can be required to be more directional. However, that may represent additional problems in acquisition and tracking (for between moves).

The high-data-rate links need to operate in a LOS mode in several different directions, although one direction at a time. This means that it is not necessary for the operator to orient the system very precisely to communicate, such that the link can sustain an angular misalignment of at least 1 deg. However, more precise aiming to improve link connection would be an additional asset.

A.4.1 Wideband Link

The Wideband Link is a medium-range (3–5 km), directional, vehicle-mounted or fixed, high-data-rate, and traffic digital data link (see section 3.1.3).

The data link will require 2 Mbps throughput to replace the throughputs of lines connecting the command post to an antenna farm.

The BER requirement for this data is $\leq 10^{-4}$, which is neither noisy nor very clean.

A.4.2 LAN/WAN Backbone

The high-data-rate LAN/WAN Backbone is a short-range ($\leq$1.0 km), semidirectional, transportable, data link (see section 3.1.2).

Until a specific LAN operating system (such as MTS) is defined for the USMC, the Banyan VINES LAN will be used to operate the LAN/WAN Backbone. The link will be a 1-Mbps link connecting a server computer to either a terminal computer or another server computer.

The BER requirement for this data is $\leq 10^{-4}$, which is neither noisy nor very clean.

A.5 ENVIRONMENTAL TESTING

A.5.1 Ozone

An ISRC link based on UV radiation is expected to operate in an urban environment, that is, the ozone concentration is between 30 to 100 ppb [Yen, 1987a]. A nominal ozone level of 50 ppb is to be expected in a test.

A.5.2 Fog

An ISRC link should be able to operate in thin fog. However, the definition of 'thin fog' is imprecise because fog density depends on particulate density and size (see figure A-1). Therefore, thin fog is taken here to mean a fog in which the visibility is 1 km.

A.5.3 Rain

An ISRC link should be able to operate in light rain, which is taken here to mean a rain rate of 1 inch/hour or less.

A.5.4 Noise Sources

An ISRC UV link is expected to operate during daylight in the presence of noise sources such as arc-welding, flames, and explosions (at the same distance from the receiver as the transmitter).

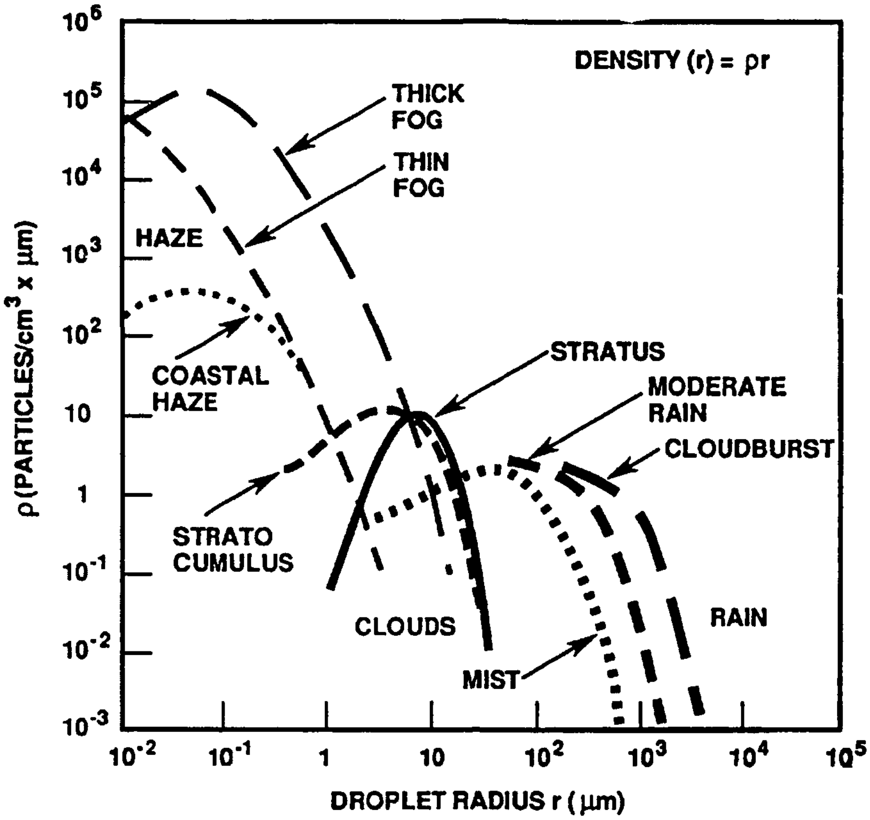


Figure A-1. Atmospheric particulates distribution.

An ISRC MMW link is expected to operate during daytime in the presence of radio frequency (RF) sources likely to exist in a battlefield.

An ISRC IR link is expected to operate during daylight in the presence of noise sources such as flames and explosions (at the same distance from the receiver as the transmitter).

A.5.5 Foliage and Obstructions

The low-data-rate ISRC links are expected to operate in spite of foliage and obstructions between the transmitter and the receiver. Precise definitions are unavailable since the test sites are unknown at this date.

APPENDIX B—SAMPLE UV LINK BUDGETS

CONTENTS

TABLE

B.1 EXPECTED UV SIGNAL

The following equation is derived empirically from the data and experience of the UV communication efforts. This equation is not theoretically rigorous and is only meant to be a rule-of-thumb formula for an order-of-magnitude estimate of the UV signal after propagating through the atmosphere.

B.1.1 Signal Formula

The number, N, of UV photons detected is approximated by the following equation:

$$N = N_0 A^{-1} \Theta_T \Theta_R F_T F_R G_s e^{-\gamma D} e^{-\sigma D} \quad \text{(B-1)}$$

B.1.2 Parameter Definitions

N_o is the number of UV photons per signal pulse emitted into the area A (cm^2), which is a function of the link distance d (km).

The mean photon path length D (km) is the expected path length travelled by single-scattered photons.

Θ_T and Θ_R are the loss factors of the transmitter and receiver, respectively, due to its orientation ($\approx$0.1 if vertical and 1.0 if horizontal in the direction of the receiver or transmitter, respectively).

F_T and F_R are the loss factors due to transmission of the signal through transmitter and receiver filters, respectively.

G_S (cm^2) is the scattering gain factor from the detection of scattered photons by a wide field-of-view (FOV) sensor.

$\gamma = 0.03 * \delta$ (km^{-1}) is the absorption coefficient due to ambient ozone concentration δ [ppb]. Urban ozone level of $\delta \approx 50$ ppb is a reasonable estimate, so $\gamma \approx 1.5$ km^{-1}.

$\sigma \approx 2$ km^{-1} is a reasonable estimate of the scattering coefficient due to gases and aerosols in the atmosphere.

B.1.3 Time Spreading

B.1.3.1 Company Radio. Assuming single scattering, the maximum likely path length travelled by a Company Radio photon is about 1500 m for d = 500 m, resulting in a path difference of $\Delta x \approx 1000$ m ($\Delta t \approx 3.5$ μs). However, the most likely path length is only about 700 m, resulting in $\Delta x \approx 200$ m ($\Delta t \approx 0.75$ μs).

B.1.3.2 LAN Backbone. Assuming single scattering, the maximum likely path length travelled by a LAN Backbone photon is about 1700 m for d = 1000 m, resulting in a path difference of $\Delta x \approx 700$ m ($\Delta t \approx 2.3$ μs). However, the most likely path length is only about 1200 m, resulting in $\Delta x \approx 200$ m ($\Delta t \approx 0.75$ μs).

B.1.3.3 Wideband Link. Assuming single scattering, the maximum likely path length travelled by a Wideband Link photon is about 3300 m for d = 3000 m, resulting in a path difference of $\Delta x \approx 300$ m ($\Delta t \approx 1$ μs). However, the most likely path length is about 3000 m because it needs to be LOS, so that $\Delta x \leq 100$ m ($\Delta t \leq 0.33$ μs).

B.2 UV COMMUNICATION SIGNAL ESTIMATE

The equation (B-1) is checked by computing the expected UV photon count per pulse for the UV communications link.

B.2.1 Experimental Data

The UV communications link used two 25-W germicidal lamps that generate 10 W of UV radiation at 254 nm. The pulsewidth of 417 μs results in pulse energy of 4.2 mJ, or $N_o = 5.3 \times 10^{15}$ photons per pulse.

The link distance was $d \approx 0.78$ km, and the mean path was then $D \approx 1.3$ km.

The transmitter and receiver orientations were both vertical ($\Theta_T = 0.1$ and $\Theta_R = 0.1$), so that the photons are distributed into a hemisphere of radius D, resulting in an area of $A \approx 3.8 \times 10^{10} cm^2$.

The transmitter did not have a filter ($F_T = 1.0$). The UV sensor had a 10%-transmission filter ($F_R = 0.1$) and a very wide FOV ($G_S \approx 10$ cm^2).

An ozone concentration of $\delta = 50$ ppb was common in the vicinity of NRaD, so $\gamma \approx 1.5$ km^{-1} is reasonable.

B.2.2 Experimental Results

Substituting the data of section B.2.1 into equation (B-1) results in N = 14.7 photons per pulse, which compares well with the experimental pulse count of about 12 to 16 photons per pulse. Therefore, equation (B-1) is probably a good and simple first approximation for signal received.

B.3 UV LASER LINK ESTIMATES

B.3.1 Expected Link Parameters

The laser is expected to output 0.2 mJ of UV radiation at about $\lambda = 266$ nm, resulting in $N_o = 2.7 \times 10^{14}$ photons per pulse.

The laser beams will essentially be horizontal and aimed at the receiver ($\Theta_T = 1.0$). The receiver orientation will still be vertical ($\Theta_R = 0.1$).

The coupling loss with an optical fiber is about 4 dB. Since the fibers are short (several meters), the path loss through the fiber (several dB/km) is likely negligible. Therefore, the transmitter filter loss in equation (B-1) is $F_T \approx 0.25$.

Assume use of the UV communication sensor ($F_R \approx 0.1$ and $G_S \approx 10\ cm^2$).

B.3.1.1 Company Radio. Assume that the laser pulse is divided into 12 directional beams to achieve omnidirectionality, there will be $N_o = 2.2 \times 10^{13}$ photons per pulse.

The link distance of $d \approx 0.5$ km results in a mean path length of about $D \approx 0.8$ km (this is an overestimation for horizontal transmission).

Assuming a beam spread of 20 deg, the area covered by a beam from each fiber will be $A \approx 1.2 \times 10^9 cm^2$.

B.3.1.2 LAN Backbone. The link distance of $d \approx 1$ km results in a mean path length of about $D \approx 1.2$ km (this is likely an overestimate for horizontal transmission).

Assuming a beam spread of 5 deg, the area covered by a beam from each fiber will be $A \approx 2.4 \times 10^8 cm^2$.

B.3.1.3 Wideband Link. The link distance of $d \approx 3$ km results in a mean path length of about $D \approx 3.2$ km (this is likely an overestimation for horizontal transmission).

Assuming a beam spread of 1 deg, the area covered by a beam from each fiber will be $A \approx 8.6 \times 10^7 cm^2$.

B.3.2 Expected Signal

The number of photons arriving at a receiver site is expected to be small, ranging from a few to several hundreds. However, the great number of photons in the vicinity of the transmitter will overload the PMT used in the UV communications sensor, so the colocating of UV transmitters may result in signal interference. Therefore, such colocation must be coupled with some form of automatic gain control (AGC) in the detection system.

B.3.2.1 Company Radio. Using the parameters of sections B.3.1 and B.3.1.1 in equation (B-1) results in a UV signal of $N \approx 28$ photons per pulse. This number of photons is sufficient to discriminate between signal and noise (see appendix E).

B.3.2.2 LAN Backbone. Using the parameters of sections B.3.1 and B.3.1.2 in equation (B-1) results in a UV signal of $N \approx 420$ photons per pulse. This number of photons is more than enough to discriminate between signal and noise (see appendix E).

B.3.2.3 Wideband Link. Using the parameters of sections B.3.1 and B.3.1.3 in equation (B-1) results in a UV signal of $N \approx 2$ photons per pulse. This number of photons is insufficient to discriminate between signal and noise (see appendix E).

B.3.3 Solid State Detectors

With some of the high number of photons computed in section B.3.2, a solid-state photodiode detector can be considered to replace the relatively expensive PMT.

The difficulty is that photodiodes are not as sensitive as the PMT. Photodiodes have dark currents of about 0 2 μA, which is equivalent to about 1.25 million UV photons in a pulse. Therefore, photodiodes probably will not work except for very short distances in the near future.

B.3.4 Interference Filter

With some of the high number of photons computed in section B.3.2, a less effective UV passband filter, such as an interference filter, can be used. Such a filter will have a narrower FOV (smaller G_S), better filter transmission (greater F_R), and more out-of-passband filter noise (N_F).

Using a PMT of lower cost will probably increase the detector dark noise, N_D.

Modify equation (B-1) by including the filter and detector noises:

$$N = N_0 A^{-1} \Theta_T \Theta_R F_T F_R G_s N_D N_F e^{-\gamma D} e^{-\sigma D} \tag{B-2}$$

Using reasonable link parameter estimates ($F_R \approx 0.3$, $G_S \approx 2$ cm^2, $N_D \approx 0.5$, and $N_F \approx 0.5$), the received signal will be on the order of $N \approx 4$ {63} photons per pulse for the Company Radio {LAN Backbone}. This signal level is not quite sufficient for determining a pulse for the Company Radio, but more than sufficient for the LAN Backbone.

B.3.5 Environmental Effects

Losses due to environmental factors will reduce the received signal considerably.

B.3.5.1 Pollution. High levels of pollution will increase the ozone concentration δ, that is, γ may be as great as 6 km^{-1} for δ = 200 ppb (pollution alert) in equation (B-1).

B.3.5.2 Fog. Fog will increase the scattering coefficient, so that σ may be as great as 6 km^{-1} for dense fog in equation (B-1).

B.3.5.3 Rain. A moderate level of rain will likely reduce the signal by a factor of two, that is, the scattering gain G_S is reduced by half.

B.3.5.4 Obstructions. Since the UV link detects scattered photons, the link can operate in the NLOS mode with a loss factor of up to 10 dB (Θ = 0.1 for vertical orientation).

B.4 DETECTABILITY

For detectability, it will be assumed that the hostile forces will possess sensors equal in capability to the UV communications sensor. Also, assume line-of-sight (LOS) configuration for the greatest distance possible. Therefore, $\Theta_R = 1.0$ and $D \approx d$ in equation (B-1), and the received photons are shown in table B1. Note that the detector dark noise is about 2400 photons per second.

The intercept range, where the signal can be received and deciphered, depends on the type of transmitter. Each transmitter has its own optics (which determines N_o) and divergence (which determines A^{-1}). The maximum intercept range for all three ISRC links is then 3.5 km.

Similarly, the detection range is the distance at which the signal will be below the noise level. The maximum direction-finding (DF) range for all three ISRC links is 4.5 km.

Table B1. Expected UV laser DF range.

	Photons per Pulse		
Distance (km)	Company Radio	LAN Backbone	Wideband Link
0.5	999	200K	5M
1.0	43	8K	200K
1.5	3.4	658	16K
2.0	0.33	64	1608
2.5	0.036	7.2	179
3.0	4×10^{-3}	0.86	22
3.5	6×10^{-4}	0.11	2.8
4.0	7×10^{-5}	0.015	0.37
4.5	1×10^{-5}	2×10^{-3}	0.05
5.0	1×10^{-6}	3×10^{-4}	7×10^{-3}

APPENDIX C—UV LASER SAFETY ISSUES

CONTENTS

FIGURES

TABLES

C.1 INTRODUCTION

The Naval Command, Control and Ocean Surveillance Center, RDT&E Division (NRaD) has developed and demonstrated the feasibility of non-line-of-sight (NLOS), covert, short-range communication links that use the ultraviolet (UV) radiation in the solar-blind region of the electromagnetic spectrum [Yen, Moberg, Gibeson, 1987]. This solar-blind region extends from wavelengths of 220 nm to 280 nm, and is formed by the existence of the ozone layer in the upper atmosphere. The ozone molecules there will absorb almost all of the solar radiation in the spectral region, so that there is no solar noise, at sea level that is, day and night are indistinguishable.

The lack of solar noise allows the detection of very small UV signals (counting individual UV photons), so that the small number of scattered UV photons can be used to transmit information. The use of these scattered UV photons results in an NLOS data link that can operate around obstacles. The ambient ozone levels that exist at sea level adds a negative exponential absorption term to the atmospheric extinction of UV radiation, so that UV radiation should be totally attenuated at short distances, resulting in covert communications.

Currently, NRaD is developing a communications link based on a UV laser. This appendix will describe the hazards associated with the use of UV sources and suggest preventive measures to be instituted for the protection of personnel operating UV systems. This appendix is an update of TD 1187 that will concentrate on the hazards of 266 nm radiation, since it is the principal wavelength used in the current UV system.

C.2 SKIN

The most well-known effect of UV radiation on the human body is the "tanning" process on the skin, which is caused mainly by UV between 280 nm and 350 nm (UV-B and UV-A; see figure C-1 for UV band definitions). The short-penetration depth of UV radiation through the human skin (see figure C-2) restricts the effects of the 266 nm radiation to the epidermis. Therefore, much of the damage to the skin is thermal.

Note that persons taking certain medications photosensitize the skin, elevating the effect of UV exposure [OSHA, 1991].

C.2.1 Short-Term Effects

The short-term effects of UV radiation on the human skin are in four stages:

(a) The darkening of melanin pigment that already exists in the epidermis. This effect results mainly from exposure to UV-A, and is commonly known as "quick tanning."

(b) Erythema, caused mainly by UV-B and UV-C (see figure C-3 for the erythema response of the human skin to UV radiation). The symptoms appear after a latency period that varies inversely to the exposure dose (2–10 hours), and

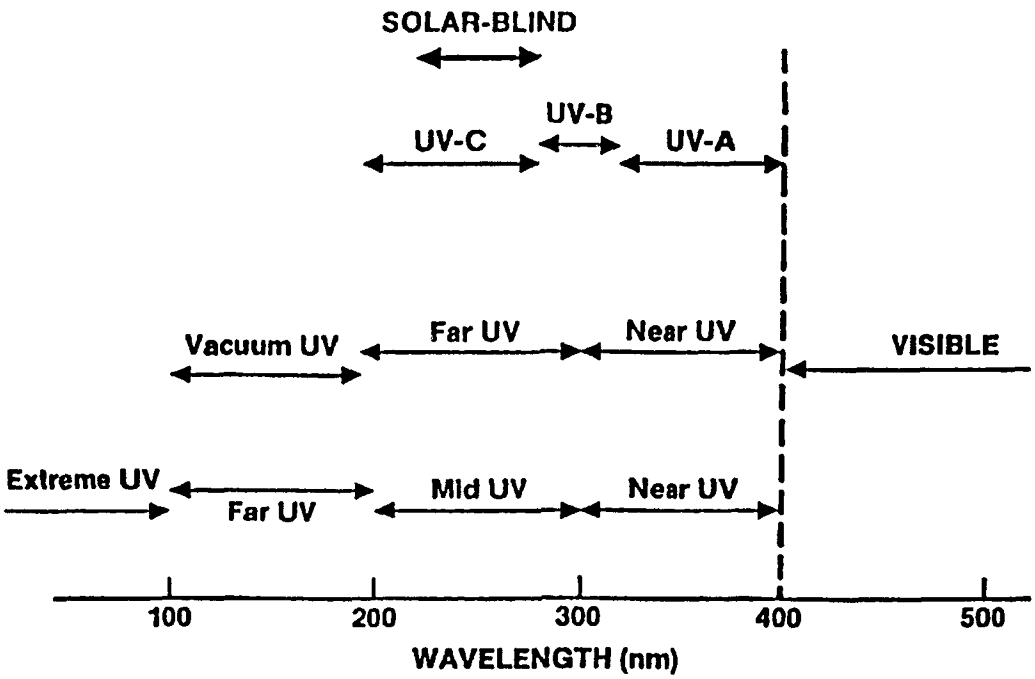


Figure C-1. Classification of UV radiation.

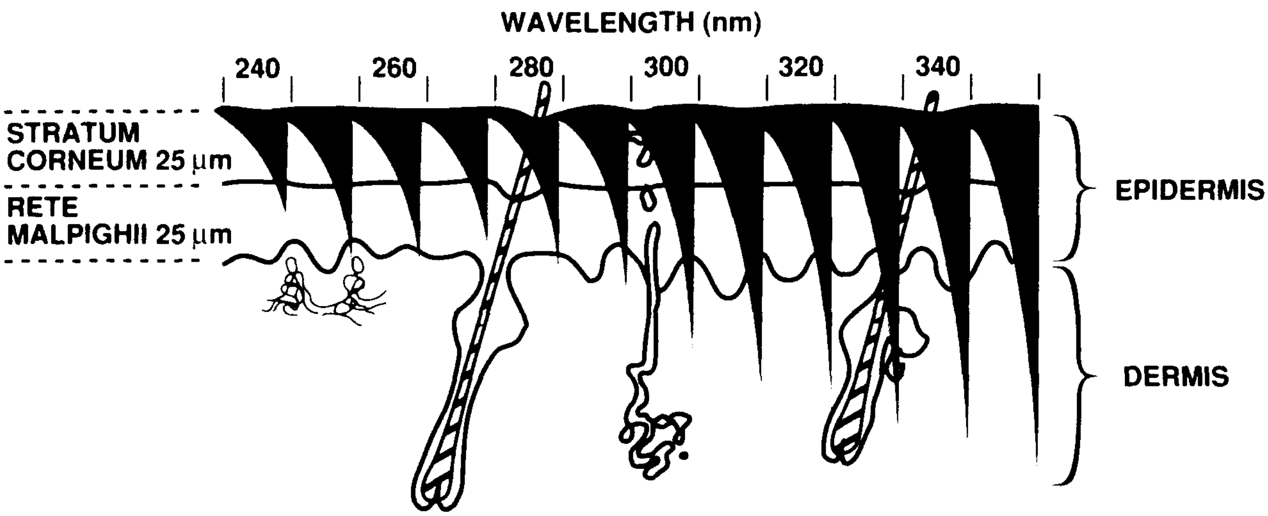
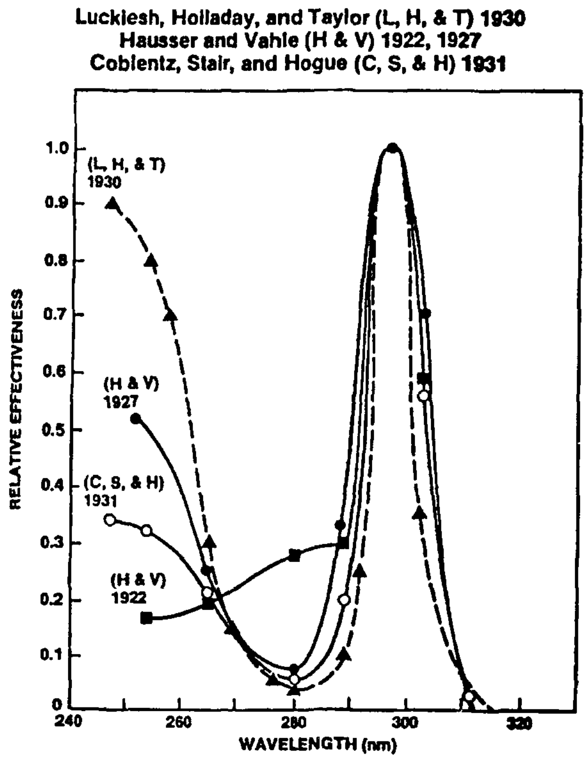
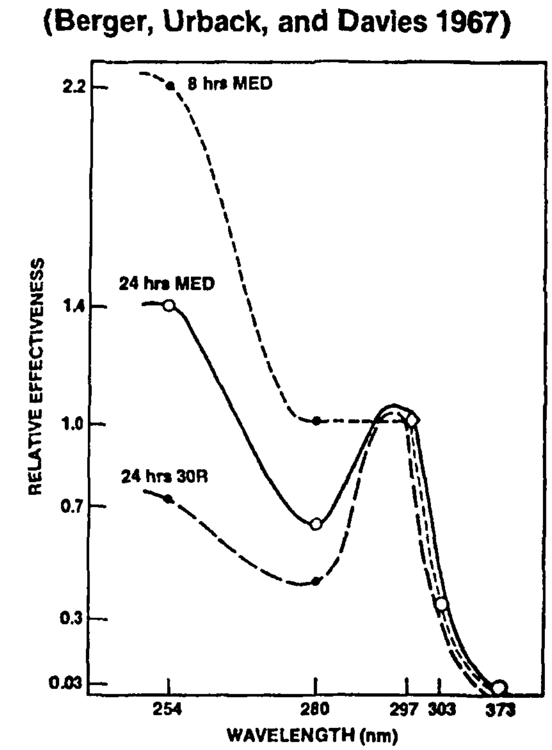


Figure C-2. Penetration of UV radiation through skin.



(a) ERYTHEMA ACTION SPECTRA



(b) ERYTHEMA ACTION SPECTRA II

Figure C-3. Erythema action spectra.

remain for a period proportional to exposure (1 to several days). Erythema results in increased flow of blood to the skin area (swelling), increased vascular permeability (blisters), and the production of toxic substances in the skin, with the severity proportional to the degree of exposure. This effect is generally known as "sunburn," and can be quite painful for several days.

(c) Increase in skin pigmentation ("suntan") by the spreading of the existing pigment granules and the production of new pigment granules. This process is caused by the same UV exposure as with erythema, and occurs within days of the exposure.

(d) Changes in the epidermis, such as thickening of the skin and "scaling." After exposure to UV radiation, skin cell growth stops for about a day, then increases to an abnormal rate for several days. The excess cellular material is shed in the process known as "scaling," and the thicker remaining skin will then be less sensitive to future UV exposure.

C.2.2 Long-Term Effects

The long-term effects of UV radiation exposure are the degeneration of the skin (premature skin aging) and an increased risk of skin cancer. The most common forms, basal cell carcinoma and squamous cell carcinoma, result from chronic exposure to UV-B radiation in sunlight and are usually nonfatal. The serious form of skin cancer, malignant melanoma, can be fatal if not treated in time.

The long-term risk is additive, that is, proportional to the total length of exposure to UV radiation.

C.3 EYES

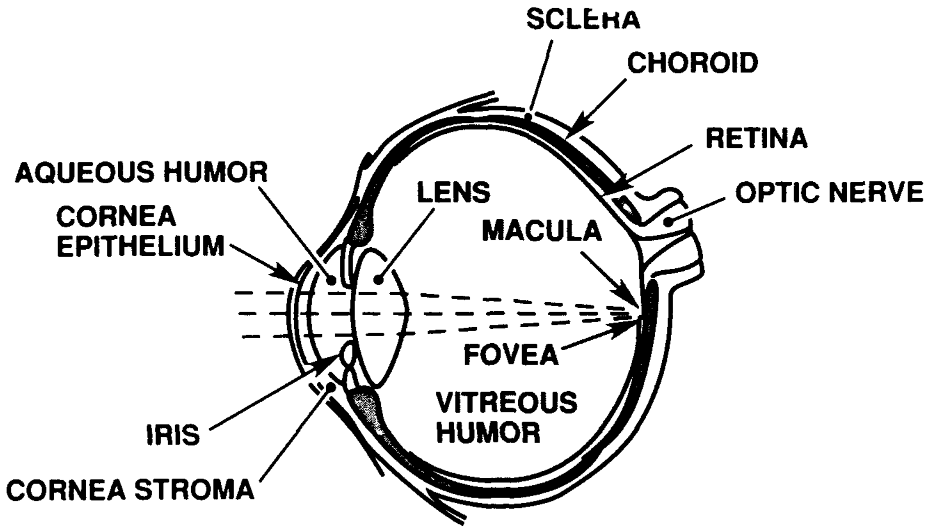
Exposure of the human eye to UV radiation leads to the inflammation of the cornea (photokeratitis) and the eyeball membrane (conjunctivitis), resulting in the condition that is commonly called "snow-blindness" or "welder's flash" (kerato-conjunctivitis). Since all of the UV radiation at 266 nm is absorbed thermally by the cornea (see figure C-4) and the outer layer of the eyeball, there is no damage to the inner ocular structure.

C.3.1 Symptoms

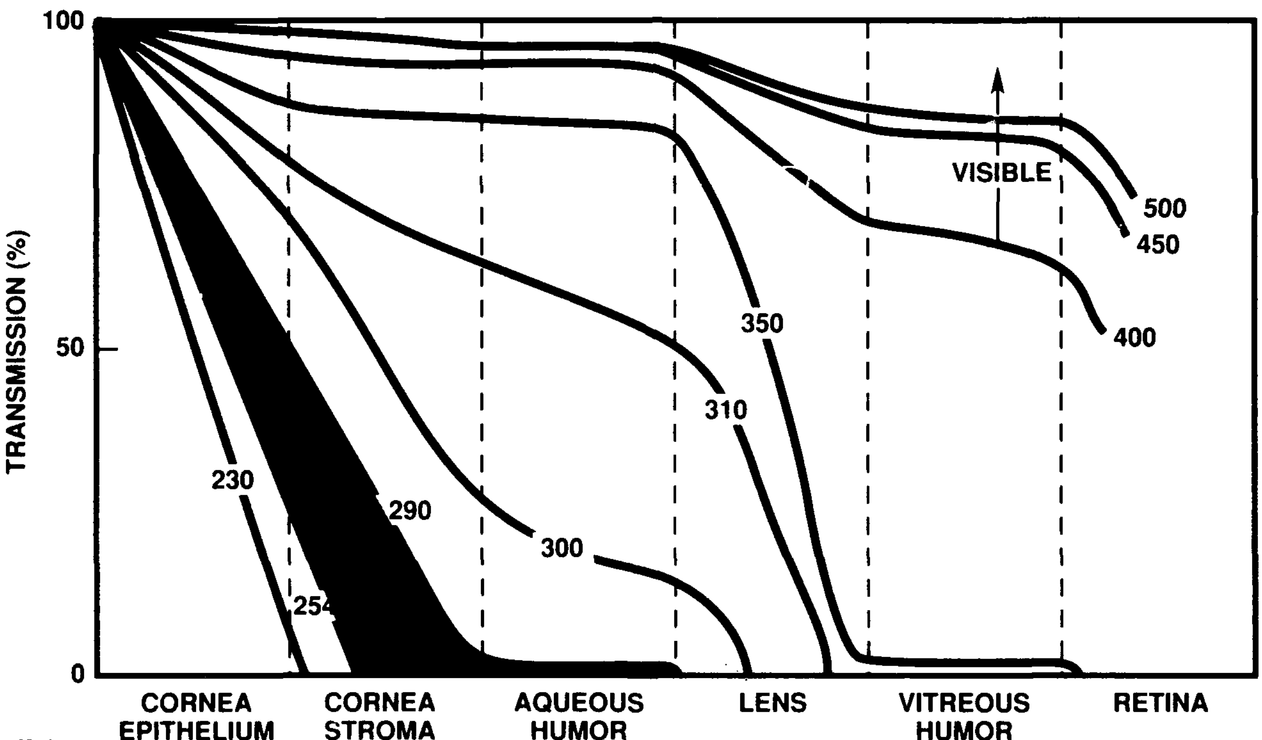
Kerato-conjunctivitis also has a latency period inversely proportional to exposure (2–24 hours) and lasts for a period proportional to exposure (1–5 days).

The symptoms are a feeling of sand on the eye, sensitivity to light, excessive formation of tear and eyelid twitching. This condition also incapacitates vision to some degree, depending on the exposure and the individual involved. Although kerato-conjunctivitis usually results in no permanent eye damage, the acute symptoms will be quite painful.

Cross section of the human eye



(a)



(b)

Figure C-4. Transmission of light through the eye as a function of wavelength.

There is a possible correlation between long-term UV exposure and an increased incidence of certain types of cataract.

C.3.2 Exposure Standards

The exposure standards for UV radiation have been made with eye exposure in mind, since the eye has greater sensitivity than the skin to UV radiation and the effects are more acute and severe.

The maximum dose of 266-nm UV radiation for daily 8-hr occupational exposure is 4 mJ/cm^2 (see figure C-5), which is equivalent to an average UV intensity of 0.14 μW/cm^2. This UV intensity translates into 1.7×10^{11} UV (266 nm) photons per square centimeter per second, which is orders of magnitude higher than the intensities detected at the receiving end of the current systems (10^4 to 10^7).

The maximum dose of broadband UV radiation for daily 8-hr occupational exposure is 3 mJ/cm^2 [NIOSH, 1972], which is equal to an intensity of only 0.1 μW/cm^2. This limit is rather conservative in that the broadband UV background can often exceed it on sunny and cloudless days in San Diego (see the next section for more details).

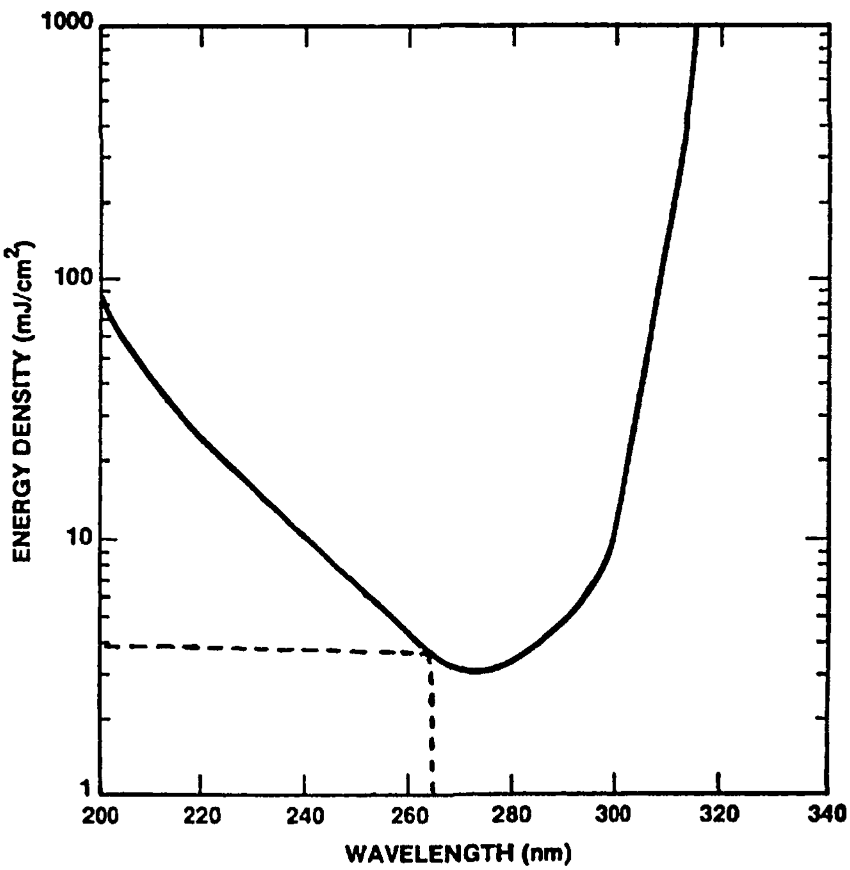


Figure C-5. NIOSH standard for exposure to UV radiation (8-hour dose).

C.4 EXPOSURE

The personnel near UV communication systems may be exposed to considerable levels of UV radiation. As to be expected, the most intense UV exposure occurs when in line-of-sight (LOS) of the transmitting laser.

C.4.1 UV Laser Link

The pulse energy of the UV laser is about 0.2 mJ per pulse, so 20 pulses of the laser directly into the eye at close range ($\leq$4 m) will reach the exposure limit. This is assuming that the eyeball has radius of 1 cm and the laser beam has divergence of 2.5 mr, so that the beam radius equals the eyeball radius at a distance 4 m from the laser.

At greater distances, the beam will be larger than the eyeball, so the actual energy impacting on the eye will be ($16 * 0.2/d^2$ or $3.2/d^2$) mJ per pulse. Assuming this relation and 1-second exposure (2400 pulses), then the safe distance is about 44 m for direct exposure.

C.4.2 UV Reflections

Reflecting surfaces near the transmitter may reflect UV radiation toward personnel who are not in view of the front of the transmitter. Such reflected UV radiation is hazardous since UV is invisible to the human eye. Reflectances (at 253.7 nm) for different surfaces vary (see table C1), so that the proposed environment of any future UV transmitter must be studied for safety purposes.

C.5 PROTECTION

The absorption of UV radiation by the ozone layer is so effective there is almost no natural background in the solar-blind region, which makes the whole concept of UV communications possible. The UV sources that can cause problems with communication are man-made, such as flames and arc-welding, which have components in the solar-blind region.

The lack of strong natural UV sources has resulted in less attention being paid to the hazards of occupational exposure to UV radiation. Unfortunately, the UV exposure latency period lasts from 1 to several hours, so that the symptoms (see table C-2) do not appear until too late. UV-sensitive equipments are necessary to warn against the presence of UV radiation since UV is invisible to the human eye. Therefore, the best protection against exposure to UV radiation is by taking preventive measures whenever UV systems are deployed.

Table C1. Surface reflectance of 253.7-nm radiation.

Surface Material	Reflectance* [%]
Aluminum, etched	88
Aluminum foil	73
Chromium	45
Nickel	38
Tin-plated steel	28
Silver	22
Stainless steel	20–30
White wall plaster	40–60
S. W. white Decotint paint	33
White cotton	30
White paper	25
Wallpaper (5 samples)	18–31
White water paints	10–30
White oil paints	5–10
White porcelain enamel	5
Flat black Egyptian lacquer	5
Smoked magnesium oxide	93
Pressed calcium carbonate	78
Pressed magnesium oxide	77
Barytes	65
Titanium oxide	6
Glass	4
Pressed zinc oxide	3

* Values obtained at normal incidence.

Table C2. UV exposure symptoms.

Kerato-Conjunctivitis Symptoms (snow-blindness, welder's flash)	**Erythema Symptoms** (suntan, sunburn)
• Gritty feeling on the eyeball • Sensitivity to light • Excessive tearing • Twitching eyelids	• Darkened skin • Blisters • Swelling • Scaling • Acute skin pains • Thickened skin
Appears 1–24 hours after exposure Lasts for 6–48 hours	Appears 6–48 hours after exposure Lasts for several days

C.5.1 Glass

Ordinary window glass (3 mm thick) will block out almost all UV radiation shorter than 300 nm (see figure C-6), so that being indoors will remove the risk of exposure (the UV transmitter must be operated outdoors).

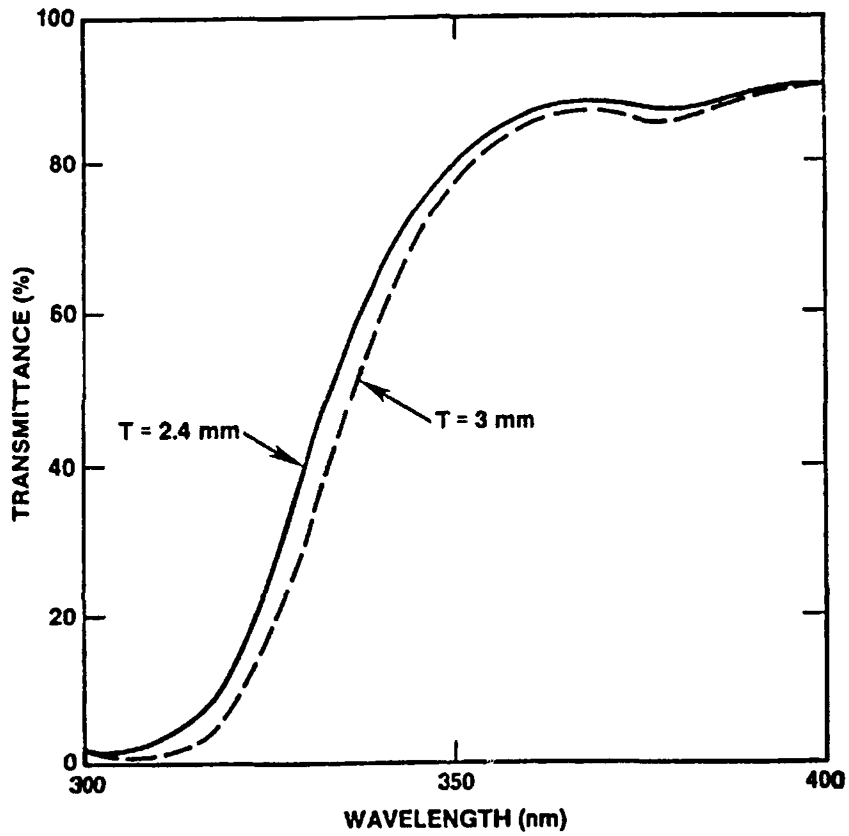


Figure C-6. UV transmission through window glass of thicknesses 2.4 mm and 3 mm.

C.5.2 Plastic

Plastic materials will block UV radiation as effectively as glass, so eyewear made from glass or plastic should be sufficient protection from UV radiation (see figure C-7). The visitor's glasses noted in figure C-7 are made from clear plastic and are used to protect visitors in workshops, and are quite effective protection against both UV-B and UV-C. The UVP glasses are made of yellow tinted plastic, for protection against UV radiation, and are thus effective against UV-A as well as UV-B and UV-C.

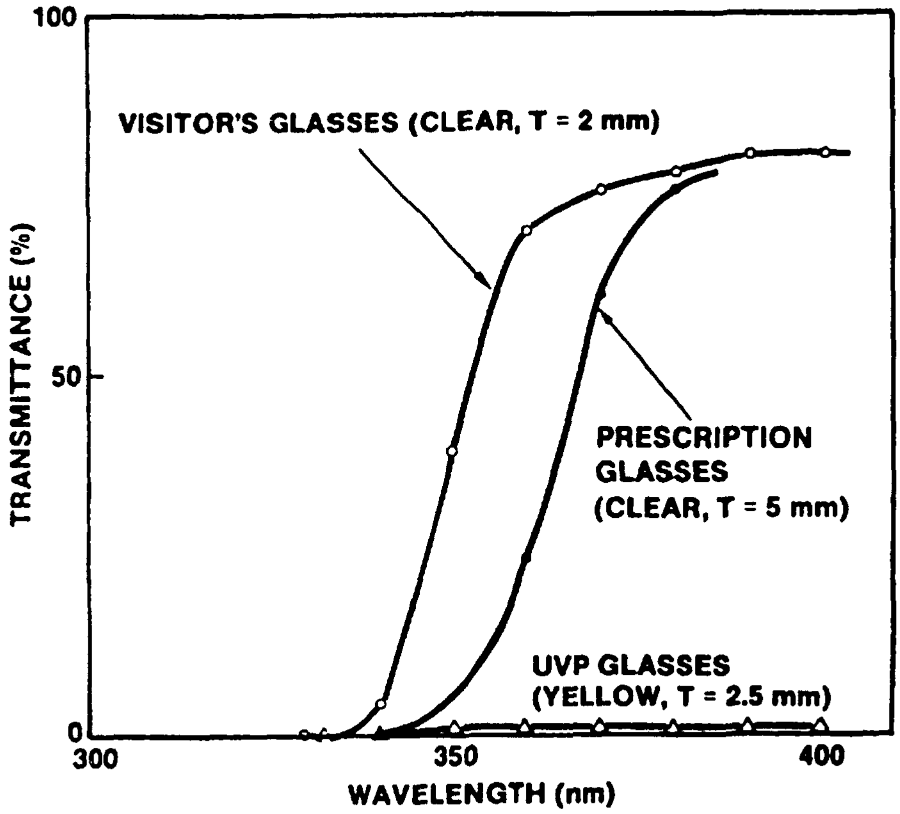


Figure C-7. UV transmission through eyewear.

C.5.3 Clothing

To protect against exposing the skin to long-term UV exposure, personnel working near UV transmitters should wear lightweight, long-sleeved clothing that covers most body surface areas. Generally, most common fabrics would be sufficient to protect skin areas (see table C3 for transmissivities to 253.7 nm radiation).

Anyone working on the transmitter while it is still transmitting should also wear a face cover, in addition to protective goggles and gloves, to prevent erythema and kerato-conjunctivitis from the high UV intensity at the transmitter.

C.5.4 Prevention

In general, UV equipments can be operated safely if simple safety measures are prescribed for that particular environment and then followed correctly. As discussed in the previous section, the danger from the transmitter is reduced considerably when not in LOS of the transmitter. Thus, a simple precaution against hazardous exposure is to place the UV transmitter (emitting point) on the top of the highest local structure, with the emitter face angled upward.

Table C3. UV transmissivity of fabrics.

Material	Transmissivity [%]
Batiste, white (muslin)	50
Cotton voile	37–43
Crepe de chine, light grey	32.5
Kapron	31
Kapron and nylon	26.6
Nylon	25–27
Silk stockings	25
Cotton stockings	18
Stockinet	14–16.5
Linen, white coarse	12
Rayon stockings	10.5
Satin, beige	10
Linen cambric	8–9.5
Rayon linen	3.8–5.3
Wool stockinet	1.4–2.8
Flannelette	0.3
Poplin	0

APPENDIX D—SAMPLE MMW LINK BUDGETS

CONTENTS

TABLE

D.1 NRaD MMW LINK ASSUMPTIONS

Operating wavelength (λ):	5 mm (60 GHz)
Modulation bandwidth (B):	20 KHz
Antenna beamwidth:	20 deg bicone
Transmitter power (P):	0.5 W (27 dBm)
Transmitter antenna gain:	7 dB
Receiver antenna gain:	7 dB
Receiver noise figure:	8 dB
Ambient temperature (T):	22 deg C
Oxygen attenuation:	−15 dB/km
Operating range (d):	0.5 km for Company Radio 1.0 km for LAN Backbone
Required S/N ratio:	10 dB

D.2 CLEAR AIR LINK BUDGET

D.2.1 Minimum Receiver Power Input

The minimum required receiver power input, $MinP_R$, is the sum of the signal-to-noise ratio (SNR), the noise figure, and the thermal noise (defined below). $MinP_R \approx -112.9$ dBm.

D.2.1.1 Thermal Noise. The thermal noise is defined by the following equation:

$$\tau = 30 \text{ dBm} + 10 \, \text{LOG}_{10}(k \; T \; B), \tag{D-1}$$

where $k = 1.38 \times 10^{23}$ is the Boltzmann constant. Using the values of T and B from section D.1, $\tau = -130.9$ dB.

D.2.2 Effective Isotropic Radiated Power

The transmitter effective isotropic radiated power (EIRP) is the sum of the transmitter power and the transmitter antenna gain. From section D.1, EIRP = 34 dBm.

D.2.3 Space Loss

The space spreading loss is given by the equation:

$$\text{Space Loss} = 20 \, \text{LOG}_{10}[\lambda/(4\pi \; d)]. \tag{D-2}$$

Substituting values from section D.1, Space Loss is −122 dB for Company Radio {−128 dB for LAN Backbone}.

D.2.4 Receiver Input Power

The clear air receiver input power, P_R, is defined by the following equation:

$$P_R = \text{EIRP} + \text{Receiver Antenna Gain} + \text{Space Loss} + \text{Oxygen Loss} \quad \text{(D-3)}$$
$$= 34\ \text{dBm} + 7\ \text{dB} + -122\ \{-128\}\ \text{dB} + -7.5\ \{-15\}\ \text{dB}$$
$$= -88.5\ \{-102\}\ \text{dBm}$$

D.2.5 Clear Air Link Margin

The clear air MMW link margin is the difference between P_R and $MinP_R$:

$$\text{Margin} = P_R - MinP_R \quad \text{(D-4)}$$
$$= -88.5\ \{-102\}\ \text{dBm} - -112.9\ \text{dBm}$$
$$= 24.4\ \{10.9\}\ \text{dB}$$

D.3 ENVIRONMENTAL LOSSES

Water vapor:	-0.5 dB
Light fog:	-0.5 dB
Heavy fog:	-1 dB (30-m visibility)
Drizzle:	-1 dB (0.1 in/r, figure 3.2-4)
Light Rain:	-6 dB (1 in/hr, figure 3.2-4)
Heavy Rain:	-17 dB (4 in/hr, figure 3.2-4)
Dry foliage (5 m):	-20 dB [Simmons]
Wet foliage (5 m):	-25 dB [Simmons]

D.4 LINK AVAILABILITY

The individual environmental losses of section D.3 are all less than the Company Radio link margin of 24.4 dB, so that the NRaD MMW Company Radio can operate under any of these conditions. However, adapting the NRaD MMW link for the LAN Backbone would leave a link margin of only 10.9 dB, so that it can operate only under some of these conditions.

The MMW link is expected to operate under some combinations of the losses listed above, but not others, as shown in table D1.

Table D1. Weather losses.

Weather Conditions	Loss [dB]	Company Radio Availability	LAN Backbone Availability
Drizzle	-1.0	Yes	Yes
Drizzle and heavy fog	-2.0	Yes	Yes
Heavy rain	-17.0	Yes	No
Humid and dry foliage	-20.5	Yes	No
Humid and wet foliage	-25.6	No	No
Heavy fog and wet foliage	-26.0	No	No
Drizzle and wet foliage	-26.0	No	No
Light rain and wet foliage	-31.0	No	No
Heavy rain and wet foliage	-42.0	No	No

D.5 DETECTABILITY

The link margin of +24.4 {10.9} dB in section D.2.5 is equivalent to about one {half} more kilometer of path loss and propagation spreading. Thus, the data interception range is 1.5 km from the transmitter, assuming that the hostile forces have the same equipment as ISRC.

Another 10 dB necessary to reduce the signal to noise level is equivalent to another half kilometer of path loss and propagation. So the detection range using ISRC equipment is about 2 km from the transmitter.

Assume that the hostile forces possess a directional 60-GHz receiver, which will have a maximum likely gain of about 30 dB. The total margin of 55 {40} dB is equivalent to about 2.5 {2} km, resulting in a maximum intercept range of 3 km, if the enemy knows precisely where to point the antenna. Similarly, the maximum detection range is about 4 km.

APPENDIX E—POISSON DISTRIBUTION

CONTENTS

FIGURE

E.1 POISSON STATISTICS

The small number of UV photons (5 to 100 per bin) reaching the receiver requires the use of Poisson statistics in computing signal probabilities. The probability of detecting x photons in a bin, when the average photon count is y photons per bin, is given by the following equation:

$$P_y(x) = y^x e^{-y}/x! \tag{E-1}$$

E.2 ERROR PROBABILITY

Given an average signal level of s photons per bin and an average noise level of - photons per bin, the error probability is defined as the sum of probabilities that the noise count in any particular bin can be greater than or equal to the signal count in the pulse bin:

$$E(s, \eta) = \sum_{z=0}^{\infty} \{P_S(z)\, P_\eta\, (x \geq z)\} \tag{E-2}$$

$$= \sum_{z=0}^{\infty} \left\{ P_S(z) \left[\sum_{x=z}^{\infty} P_\eta\, (x) \right] \right\}$$

$$= e^{-s}\, e^{-\eta} \sum_{z=0}^{\infty} \left\{ (S^Z/z!) \left[\sum_{x=z}^{\infty} (\eta^x/X!) \right] \right\} \tag{E-3}$$

The error probabilities, given average signal and noise levels, are shown in figure E-1. Note that the error probability is exponential with respect to the signal level.

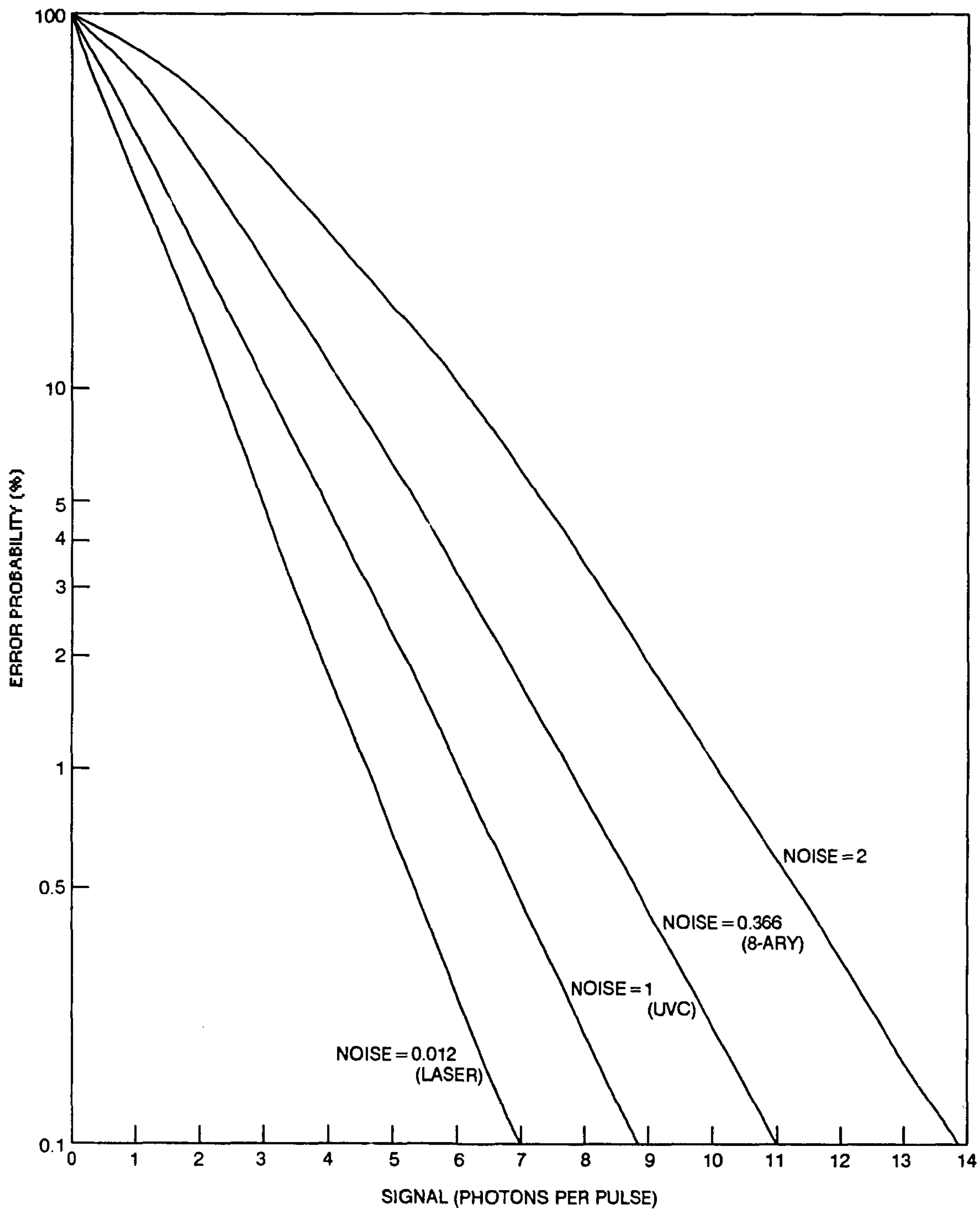


Figure E-1. Poisson error probability.

APPENDIX F—HUGHES EHF APPLIQUE SPECIFICATIONS

Operating frequency:	54 GHz
VHF/UHF input:	30–400 MHz
Modulation bandwidth:	20 kHz
Antenna type:	45-deg bicone
Polarization:	vertical
Output power:	1 W
Receiver noise figure:	≈8 dB
Operation range:	≤4 km
Detection range:	8 km
Power used:	≈28 VDC
Operating temperature:	-20 deg C to 50 deg C
Cost:	$110K per unit
Compatible radios:	AN/URQ-33 (JTIDS) AN/VRC-46 AN/VRC-64 AN/VRC-87 (SINCGARS) AN/VRC-94 (Harris) AN/WSC-3

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This document is an exploratory development (6.2) plan for the Intentionally Short-Range Communications (ISRC) project. The USMC requirements and project objectives are quantified, then possible solutions identified and developed. Some of these ideas will be attempted to determine the best option(s) satisfying the USMC requirements.

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