AN ELECTRODELESS ULTRAVIOLET COMMUNICATIONS SYSTEM

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The Laser Communications Laboratory (LCL) of the Wright Laboratory Avionics Directorate is heavily involved in designing optical communications systems covering the full optical spectrum to meet our current and future military communications requirements. This paper summarizes the in-house designed and built solar blind ultraviolet communications system used in the LCL to investigate non-line-of-sight data and voice links. It also summarizes some of the previous DOD work accomplished to exploit free space communications via ultraviolet radiation. In addition, safety factors peculiar to ultraviolet radiation in a closed cockpit environment are addressed. An evaluation of the current electrodeless ultraviolet communications system and a synopsis of planned future projects to improve the system are included in the paper.

1.0 INTRODUCTION

In the arena of covert short range communications, one exceptional area of photonic communications stands out - Ultraviolet (UV) communications. In particular, the UV band of wavelengths referred to as the solar-blind region are especially interesting. It is within this band that background noise caused by solar radiation is very effectively blocked by the earth's atmosphere. It is the purpose of this paper to discuss the Wright Laboratory, Communications Technology Group's efforts in solar-blind, non-line-of-sight UV communications.

The attraction of UV communications to the Air Force (AF) is primarily due to the following reasons: precise beam pointing and tracking are not as critical as in other forms of photonic communications, UV has propagation extinction properties which enable short range covert communications, and photonic communications provides a means of wireless connectivity. For UV communications to become practical, reliable, and supportable, device technology advancements are needed. UV sources and detectors must use low power, be light weight and inexpensive for system development and deployment. Additionally, atmospheric conditions, as they vary across the globe, through the seasons and at varying altitudes, have significant impact on UV communications performance. Finally, with the broad

band UV sources that exist today, particular safety issues will need to be addressed concerning ozone creation, UV radiation dangers, and the degradation of aircraft materials in the presence of ozone.

2.0 UV COMMUNICATIONS SUMMARY

Much has been accomplished in the research of UV communications, however, more is needed to develop the UV technology to the point of fielding a practical, and safe UV communication system. Over the past two decades, experiments and studies have taken place which provide some practical insight into the ability to communicate via the solar-blind UV spectrum. This work, largely sponsored by the Department of Defense (DOD), has concentrated primarily on the atmospheric channel, UV sources and detectors, background UV sources and filtering, appropriate modulation processes, and last but not least, UV radiation safety.

2.1 Atmospheric Effects on UV Communications.

Traditionally, optical communications has dealt with free space line-of-sight communications paths or optical waveguide communications (signals guided via fiber optic cables). The reason for this approach is due to the free space travel properties and the reflection properties of the wavelengths currently chosen for optical communications. As the wavelength employed grows shorter and shorter until it approaches the dimensions of aerosol or molecular particles, the potential for atmospheric signal scattering or absorption is greatly increased.

2.1.1 Absorption Properties. The primary atmospheric constituent involved with absorption is ozone [1, pg 2]. In addition, the immediate ozone concentration is the most important of all the meteorological parameters that affect UV communications link performance [2, pg 1]. Ozone density increases with altitude up to about 30 km as shown in Figure 1. Consequently, the range one is able to communicate in an airborne environment will drop inversely with the density of the ozone.

Figure 1. Seasonal variations of ozone to air ratio at Flagstaff, AZ [ref 3].

Figure 2. shows the consistency of the 30 km ozone maximum density belt at varying latitudes. The upper atmospheric ozone also provides a plus for UV communications systems operating nearer the earth. Stratospheric ozone prevents solar radiation less than about 280 nm from reaching the surface of the earth [4, pg 106] consequently providing a natural background noise filter. It is of interest to note that instantaneous ozone level measurements at near sea level in the San Diego, CA area changed by as much as one order of magnitude within a three minute period [2, pg 1]. It is quite likely that large swings in ozone concentration at normal flight altitudes could also be expected.

2.1.2 Effects of particulates. Particulates or aerosols are of highest concern near the Earth where particles such as dust can be lifted and carried in low atmospheric disturbances. This phenomenon was readily apparent in the Desert Storm campaign. These particles are large enough to reflect the short wavelengths of the UV radiation. Over the propagation path, these reflections result in a multipath effect which allows reception of the UV transmission around direct line of sight obstacles. Army scattering model theory asserts that forward scattering is predominant [10, pg 42]. In addition to particle scattering (Mie scattering), there is molecular scattering (Rayleigh scattering) effects. Some of the atmospheric molecules are large enough to scatter UV radiation and assist the non-line-of-sight properties of this communications media. Again, forward scattering is assumed to be the dominant effect.

2.1.3 Weather effects (wind, rain, temp, humidity, season...). Of particular interest in line-of-sight optical communications is the need to overcome interruptions to signal reception due to optically opaque weather

Figure 2. Latitudinal variation of ozone concentration [ref 3].

conditions. UV communications is attractive in this respect since it has the ability to scatter transmitted signals through various weather obstacles. In fact, depending on the severity, bad weather condition were noted to improve UV communications performance where other systems would be degraded [6, pg 51]. However, it is intuitive that the greater the scattering effect, the shorter the effective range of the UV communications system for a given power output. Any airborne UV communications system will likely require some form of weather or atmospheric sensing system coupled with an automatic power adjustment system, or simply a manual power adjustment with a positive link indicator since the airborne UV transceiver can be subjected to variations in the weather due to altitude changes and seasonal changes.

2.2 UV Sources. UV sources to this point have been limited almost entirely to arc discharge lamps filled with mercury or xenon for the active medium. While UV laser sources are available, they require excessive power, are inefficient, fragile, and are somewhat bulky, especially for airborne platforms. The need for a compact UV laser source suitable for UV communications has been noted to be paramount to the further development of this technology [6, pg 12][7, pg 125]. One possible laser source is the quadrupled Nd:YAG with an output at the wavelength of 266 nm. The quadrupled Nd:YAG can provide added output power in the solar-blind region to extend operating ranges while still maintaining covertness. Ideally, a smaller, lower input power, lighter and more efficient UV laser diode could be developed to provide the airborne UV transmitter source.

2.3 UV detectors. Predominantly, photo-multiplier tubes (PMTs) have been the most popular means of detecting the UV transmitted signal. Photons impinging on the photocathode of the PMT causes electrons to be

emitted which then pass through several amplifier grids to obtain useable signals. The problems with these devices are the somewhat large vacuum tube technology and the very high voltage requirements of the tubes, approximately 1000 volts. In addition, the tubes and their associated electronics are expensive. Another potential system detector is the silicon detector. These devices are small, require low power, and are light weight. However, the wavelength response region of these devices necessitates the use of extensive filters and, consequently, the cost of these devices is escalated while the efficiency is reduced. Recent developments in this area reveal that small solid state PMTs are available which operate on voltages in the range of 5 to 15 volts versus the 1000 volts for conventional PMTs. In addition, at least one of the small solid state PMTs can be obtained which is prepackaged with an internal power supply.

2.4 UV Background Signals and Filtering. The solar blind region of the UV spectrum is chosen for communications primarily due to the absence of solar UV radiation from that band penetrating the earth's atmosphere. However, there can be other sources of UV radiation which can interfere with UV communications. These sources include, but are not limited to, rocket and aircraft afterburner ignitions, lightning strokes, open flames, and arc welding flashes. Most influential of these to airborne UV communications would be aircraft afterburner ignition and lightning strokes. Since an aircraft would not normally be attempting to communicate over a UV communications link during afterburner operation, this is considered an inconsequential factor. Lightning strokes are a different matter. UV communications with intermittent interruptions due to lightning strokes may be considered an acceptable compromise should covert airborne UV communications be required for a specific mission. Numerous open flames in a war torn environment could pose a possible hindrance to airborne UV communications for low altitude and slow speed flight. Narrow bandpass filtering would be necessary to assure maximum performance is maintained without the possibility for background UV noise injection. Filters currently exist to adequately address this need.

2.5 UV Modulation Techniques. The simplest method of UV modulation is on-off keying (OOK). Various other methods have been employed to either increase system efficiencies or data rates such as pulse position modulation (PPM) or pulse frequency modulation (PFM). For the demonstration of our WPAFB UV communications system in the LCL, we use OOK with direct detection via a PMT.

2.6 UV Safety. The greatest safety threat for the UV communications system in an airborne environment is aircrew personal injury due to UV radiation. Specific radiation exposure problems include eye, skin, and ozone effects. National Institute for Occupational Safety and Health (NIOSH) standards identify the eyes as the primary UV radiation concern since they are most sensitive to UV radiation in the 200-400 nm wavelength range. For the long term exposure to the eyes, inflammation of the cornea epithelium and cornea stroma results from thermal absorption from the smallest UV wavelengths out to about 290 nm. For skin effects, erythema or sunburn effects can be caused at wavelengths in the 280-350 nm region [6, pg C-3]. Most UV sources available at this time which are available for UV communications applications are broad band emitters and as such will have radiation components in the regions of UV which can be regarded as health hazards. In addition, UV emissions in the 185 nm region actually cause ozone production [8, pg 59] which is detrimental in two ways to UV communications. First, the increased ozone concentrations pose a health risk to the aircrew. Secondly, the increased ozone increases the rate of absorption of the communications signal, possibly blocking the UV link. The NIOSH UV exposure standard is shown in Figure 3.

Figure 3. NIOSH radiation exposure standard(NIOSH 1972).

This diagram indicates the maximum exposure level for a monochromatic 254 nm wavelength source is approximately 6.0 mJ/cm² over an eight hour period. But, our UV system is a wideband UV source, so we need to consider the relative spectral effectiveness for a wideband source over the output range of the source.

This involves relating the output of the 254 nm line to the 270 nm line, which according to NIOSH is about a factor of 0.50. The measured irradiance of the LCL UV system at the 254 nm wavelength was 7.8 $\mu\text{W}/\text{cm}^2$ which corresponds to about 14 mJ/cm^2 per hour with consideration of the relative spectral irradiance factor. Consequently, by NIOSH standards, this system should be limited to roughly three hours operation in the presence of an aircrew or system operators.

3.0. WL/AAAI-2 UV COMMUNICATIONS SYSTEM

The basic UV communications system is composed of a single transmitter and a receiver subsystem. The transmitter consists of a mercury-argon, wireless (electrodeless) radio frequency (RF) excited bulb and an RF oscillator/modulator. The receiver consists of a Hamamatsu R431S, cesium-telluride (Cs-Te) photomultiplier tube (PMT) coupled with a Hamamatsu photon counter. The transmitter bulb is RF shielded by a copper wire mesh covering which was locally manufactured at Wright-Patterson Air Force Base (WPAFB). The PMT is fitted with a UV filter centered about the operating wavelength of 254 nm and having a band pass of 12 nm and a 10 % transmissivity. A Stanford Research Systems (SRS) low noise amplifier is inserted after the PMT and photon counter to provide signal filtering and amplification. Photomultiplier tube radiant sensitivity is specified to be approximately 18 mA/W at the 254 nm wavelength. Both transmit and receive subsystems are fitted with RS-232 to TTL/TTL to RS-232 converter packages to allow connection of the system to personal computers or BER test equipment. The system setup is illustrated in Figure 4.

Figure 4. LCL UV communications transmitter (a) and receiver(b).

4.0 LINK ANALYSIS

Two separate approaches to the link budget question are considered here; first, the modeling of atmospheric propagation according to Bouger's Law (or Lambert's Law): $I/I_0 = e^{-at}$ [8, pg 153] and secondly by a U.S. Navy estimate according to

$$N = N_0 A^{-1} Q t Q_r F_T F_R G_S e^{-\gamma D} e^{-s D} \quad [6, \text{pg B-3}].$$

4.1 First, the irradiant power received at the entrance pupil of the UV receiver is studied by considering Lambert's Law: $I = I_0 * e^{-at}$. Setting the attenuation variable to be represented by $(a+s)$ for absorption and scattering, then $I = I_0 * e^{-(a+s)t}$. Inserting the LCL measured value for I_0 of 7.8 $\mu\text{W}/\text{cm}^2$ and allowing the optical range or thickness, t , to vary from 0 to as much as 4 km, the following irradiance plots (Figures 5, and 6) are produced. Figure 5 uses a nominal value of 1.5 km^{-1} for absorption and scattering. A more conservative value was used in calculations for Figures 6 where absorption is 3 km^{-1} and scattering is 4 km^{-1} .

Figure 5. Logarithmic irradiance plot using attenuation factors of 1.5 km^{-1} .

Figure 6. Logarithmic irradiance plot using 3.0 km^{-1} absorption factor and 4.0 km^{-1} scattering factor.

In reviewing the Hamamatsu specifications for the R431S PMT, the PMT Equivalent Noise Input (ENI) is stated as follows:

$$\text{ENI} = [2q * I_{db} * G * df]^{1/2} / S \quad (\text{Watts})$$

where,

q = one electron charge, 1.60×10^{-19} coulombs

I_{db} = anode dark current in amperes after 15 hours storage in darkness (0.3 nA for R431S)

G = current amplification (5.0×10^5 for R431S)

df = bandwidth of the system in hertz
(usually 1 Hz)

S = anode radiant sensitivity in amperes
per watt at the wavelength of
interest (1.0×10^4 for R431S)

of d = 50 ppb was the estimate used by
the Navy)

s = the scattering coefficient due to gases
and aerosols in the atmosphere (2 km^{-1}
is the Navy estimate)

Using this expression for the PMT receiver noise, a minimum noise floor of $6.93 \times 10^{-16} \text{ W}$ is determined. Expressed in dBm we have -121.6 dBm. Assuming other noise sources are present at the receiver and that it is necessary to overcome that noise with a signal to noise ratio of 60 dB, then a signal of 691 nW/cm^2 must be available to the receiver. Then, according to Figures 5 and 6 above, we could expect a communications range of approximately 0.8 km under favorable conditions and approximately 0.3 km in a more severe environment. This estimate agrees well with signal detection in our system but not with the capability to actually communicate over these ranges. This is likely due to large losses such as occurs at the UV filter fitted to the PMT which is only 10% transmissive.

4.2 Next, we consider a link equation as determined by the U.S. Navy as expressed by

$$N = N_0 A^{-1} Q_T Q_R F_T F_R G_s e^{-yD} e^{-sD};$$
where,

N_0 = the number of UV photons per signal
pulse emitted into area $A(\text{cm}^2)$ which is
a function of link distance $d(\text{km})$

D = mean photon path length (km) -
expected path length traveled by
single-scattered photons

Q_T = transmitter loss factor due to orientation
(= 0.1 if vertical and 1.0 if horizontal in
the direction of the receiver)

Q_R = receiver loss factor due to orientation
(= 0.1 if vertical and 1.0 if horizontal in
the direction of the transmitter)

F_T = loss factor due to transmission of the
signal through the transmitter filters

F_R = loss factor due to transmission of the
signal through the receiver filters

G_s = (cm^2) the scattering gain factor from the
detection of scattered photons by a
wide field of view sensor

y = $0.03 \cdot d(\text{km}^{-1})$ the absorption coefficient
due to ambient ozone concentration
 $d(\text{ppb})$ (an average urban ozone level

In considering the Navy equation, modeling the UV signal transmission through the atmosphere, and inserting their estimates, the values shown in Table 1 were calculated for the LCL UV communications system employed in this experiment. The values obtained were based on a 254 nm wavelength output measured at 7.8 uW/cm^2 over a 3.33 ms pulse width. A moderate ozone concentration level of 50 ppb was assumed. Transmitter orientation was vertical with respect to the receiver and the receiver orientation was at approximately 45° with respect to the transmitter. A filter was not used on the transmitter (which radiated into a hemispherical area). However, a 10% transmissive filter was used on the receiver. A wide angle field of view receiver gain of $G_s = 10 \text{ cm}^2$ was assumed.

The values shown in Table 1 indicate the very limited range over which the UV communications system is predicted to operate. Navy UV sources were supplying tens to hundreds of thousands of photons per second. The bulb in use here obviously falls far short of the output theoretically required for effective and reliable optical communications. This system viewed through these parameters would appear to have a range on the order of tens of meters. This prediction has been the experience in lab tests.

Table 1. UV Communications Photon Estimates

Link Distance	Ozone Concentration	Photons Per Pulse	Photons* Per Second
250 m	50 ppb	0.232	70
100 m	50 ppb	2.235	671
75 m	50 ppb	4.769	1431
25 m	50 ppb	44.869	13,461

* Maximum value possible at 300 bps data rate

5.0 WL LASER COMMUNICATIONS LAB (LCL) UV TRANSCIVER TESTS

5.1 Spectral radiometric tests were attempted with an EG&G spectral radiometer; however, even though the radiometer was specified to be able to measure

radiated power over 200-1100 nm wavelengths, the radiometer was unable to record readings below 360 nm wavelengths. Consequently, an International Light Research Radiometer Model IL1700 was used to detect the power emitted from the LCL UV transmitter. The transmitter bulb was covered with a hood fitted with a fan and duct which removed ozone from the laboratory created from the 185 nm component of the bulb radiation. An exit aperture of approximately one square inch was cut into the hood to facilitate power measurements. The setup is illustrated in Figure 7.

Figure 7. Indoor UV transmitter power measurement setup.

The short coming in using the IL1700 was that we only had filters available which were capable of measuring the power developed at the 254 nm wavelength $\pm$ 12 nm. The power available from the bulb was measured from this setup to be 0.21 $\mu\text{W}/\text{cm}^2$. Another power measurement was performed on the balcony of the LCL using a Photodyne Radiometer, Model 33XLC, setup as shown in Figure 8. The power measured in this setup averaged about 7.8 $\mu\text{W}/\text{cm}^2$. The greater power measurement is likely due to the larger field of view with respect to the transmitter bulb since the hood was omitted in this procedure. This measurement was performed out of doors to allow natural air currents to remove ozone created by the 185 nm output of the bulb.

Figure 8. UV transmitter power measurement setup.

5.2 UV bulb pulse repetition rate tests were performed on the UV transmitter bulb with a setup as shown in Figure 9. A Stanford Research Systems DS345 signal generator provided pulses to the UV transmitter and a Tektronics 2440 Digital Oscilloscope in conjunction with the Tektronics 2402A Tekmate Computer were used to record received pulses at the receiver. Bulb pulse rates were varied from 1600 pps to 19,200 pps.

Figure 9. UV pulse width measurement setup.

The pulse rise and fall times were consistent among all the plots and were on the order of 30 microseconds. Allowing each pulse the nominal 30 usec rise and fall time and providing an additional 30 usec for pulse duration to reduce pulse aliasing; then a 90 usec pulse width would account for a maximum data rate of 11 kbps. Beyond this point, adjacent pulses would begin before the bulb had completely turned off. This is apparent from the pulse plots analyzed; once pulse rates rise above 9600 Hz, the pulse is not allowed to fully reach the off state or zero voltage level from the detector.

5.3 BER testing was carried out with an HP 4957A Protocol Analyzer/Bit Error Rate Tester (BERT). Maximum bit rate tested was 300 bps with a BER of 10^{-2} . Minimum bit rate tested was 75 bps with an associated BER of $10^{-0.8}$. Higher data rates were not attempted since data transmission results in a simple short range line-of-sight test were so poor. The test setup is identical to the system setup shown in Figure 5, with the exception that an HP 4957 Protocol Analyzer was used in place of the data source and data destination. A Qualimetrics Data Logger (QDL2000) model 1165 was used to record weather information during the test.

5.4 BER testing was also accomplished for a non-line-of-sight communications link from one side of the LCL to the other. The equipment setup was identical to that shown for the line-of-sight BER test with the exception that the LCL facility was used as a barrier to direct path reception. The bit rate used for this test was 300 bps and the BER was noted to be $10^{-0.4}$. The data was very noisy causing several clock slip errors to be present in each data block transmitted. This test was performed in

moderate to heavy fog conditions where visibility was limited to about 1/4 mile. The QDL2000 was again used to capture weather data.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Past work accomplished in researching UV properties and systems for communications applications points to the following conclusions:

6.1 Atmospheric phenomenon associated with UV energy absorption and scattering provide a benefit and a dilemma; the natural short range of transmission provides inherent covertness, but some tactical ranges are near impossible to obtain at this stage of the technology. Where atmospheric particulates and or fog are insignificant, absorption by ozone is identified as the leading communications range limiter [2, pg 1]. Where particulates or fog are quite dense, signal scattering over-shadows the ozone absorption effect [10, pg 13].

6.2 UV sources and detectors require further development for compactness, low power consumption, minimum weight, and safety. Sources and detectors should be optimized for operation in the 270 - 300 nm region [9, pg. 11].

6.3 Airborne UV communications, based on previous studies and experiments, appears to be a viable means of performing short range covert communications. However, based upon the results of the WL/AAAI test performance, and the density distribution of ozone in the atmosphere, UV communications at high altitudes could prove to be quite difficult for any critical airborne communications links. Any system design must take into account the fact that UV communications will likely degrade drastically as the altitude of operation is increased.

6.4 In addition, system operating temperature must be considered since the device used in this experiment failed to operate at temperatures below about 32 degrees Fahrenheit.

6.5 Ozone created by the 185 nm line of UV sources produce a toxic flight crew environment. Flight crew safety could be best served by avoiding UV sources with spectral radiance below the 200 nm region as well as proper shielding of skin and eyes from the UV transmission sources. Normal flight crew attire should suffice for this protection.

6.6 Future improvements would be to obtain a narrowband UV source and to take advantage of smaller, lower power PMT technologies.

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