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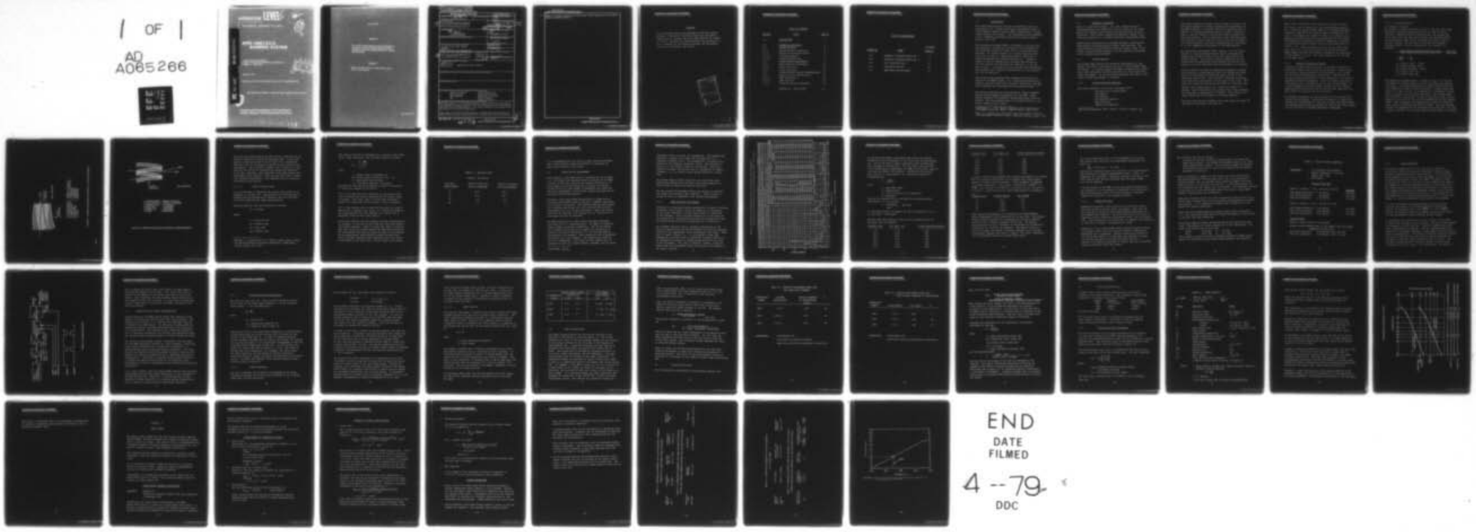

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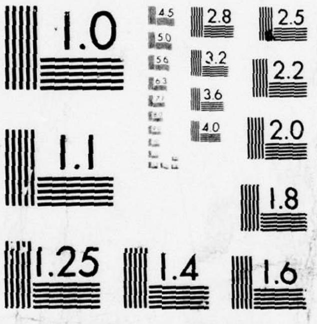

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TECHNICAL REPORT-77-2167-1

WIRE OBSTACLE WARNING SYSTEM

J. HUNT AND R. KLEEHAMMER
FAIRCHILD CAMERA & INSTRUMENT CORPORATION
SYOSSET, L.I., NEW YORK

JANUARY 1979

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

The requirements for a Wire Obstacle Warning System (WOWS) have been studied to establish the design trade offs which are compatible with the WOWS development specification DS-EH-0232A(V). The results presented in this report form the basis for the detailed WOWS design.

This report covers the System Requirements, Stabilization Requirements, and Electro-Optical Design considerations for a Flyable Exploratory Development

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CONT

Model of a Charge Coupled Device (CCD) Sensor System operating as an Automatic Pattern Recognition System.

FOREWORD

This semiannual report was prepared by Fairchild Imaging Systems, a Division of Fairchild Camera and Instrument Corporation at Syosset, New York under Contract No. DAAB07-77-C-2167. The work was performed under the direction of Mr. A. Kleider for the Aviation Research and Development Activity, Ft. Monmouth, New Jersey.

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LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

The system defined herein has been configured to meet the requirements for a flyable exploratory development model of a Wire Obstacle Warning System (WOWS) incorporating a charge coupled device (CCD) sensor. The requirements were generated in the AVRADCOM Development Specification DS-EH-0232A(V) dated 27 July 1976.

The helicopter-mountable WOWS is configured to provide real time detection, recognition and warning of the presence of wire obstacles along the flight path for nap-of-the-earth missions. The primary sensor is an image intensifier/CCD array that is used in a range-gated mode of operation to achieve background and range discrimination. A computer system is used to automatically recognize the presence of the wire obstacle by processing the "patterns" in the CCD output signal. A display unit then provides both alphanumeric data readouts and a symbolic representation of the detected wire and its position.

Two earlier Army-sponsored study programs established key inputs for the WOWS concept, i.e., the detection/recognition criteria, the CCD single site activation feasibility, and the logic algorithm for processing the wire detection data.[1,2]

This report describes the system analysis, design tradeoffs and the system component approaches for the WOWS. These efforts represent the completed "system definition" phase of program. The next planned phase of the WOWS program is a detailed "system design" effort.

---

[1] Kleehammer, R., "Wire Object Detection Study" Research and Development Technical Report, ECOM-76-0881-F, April 1978

[2] Lyon, R., "Single Site Activation Logic and Display" Research and Development Technical Report, AVRADCOM-76-0927-F, Sept. 1978

2.0 TECHNICAL DISCUSSION

There is a need for reliable, low cost, sensor system to provide detection and recognition of wire objects in the flight path of helicopters flying nap-of-the-earth missions in night conditions. This section analyzes and defines a system to provide this capability in a flyable exploratory development model.

Specifically discussed are the systems analysis, stabilization requirements and electro-optical design considerations. The electro-optical considerations include the lenses, laser transmitter, intensifier/CCD receiver, and the predicted performance of the combined system elements.

2.1 SYSTEM ANALYSIS

The present WOWS contract has specified requirements for the design, fabrication, and ground testing of a Wire Obstacle Warning System. In a future program the WOWS is planned to be tested with a UH-1 helicopter platform operating in a nap-of-the-earth (NOE) environment. In the following paragraphs the impact of NOE flight on WOWS performance is analyzed.

2.1.1 Nap-Of-The-Earth Operation

NOE flight maneuvers for the UH-1 helicopter are:[3]

- Hovering out of ground effect
- NOE takeoff
- NOE approach
- NOE downwind approach
- NOE quick stop
- Masking and unmasking

---

[3] NOE Flight Maneuvers, FMI-1 Terrain Flying, 1 October 1975

These basic maneuvers, together with the type of terrain and helicopter speed, will strongly influence the requirements on the WOWS platform. In extreme cases pilot maneuvers, such as banking or pop-up/pop-down, may require a mode of operation where a zone is "cleared" from the helicpoter's position to the range required. For an operational case provisions must also be made to either slave the line-of-sight of the WOWS to the flight direction (inertially compensating for crab angle) or to the independent requirements of the WOWS operator.

The exploratory development model, however, is to be flight tested in a restricted experimental mode to determine the feasibility of WOWS without all the real-life mission conditions present. The airborne testing of WOWS will be performed with the exploratory system mounted at the nose chin region of the UH-1 Helicopter and the procedure is as follows:

Prior to takeoff the WOWS is mechanically aligned in azimuth and elevation to predetermined angles that define the flight vector for the planned altitude and power profile of the helicopter during test. The helicopter traverses a straight line track with light markers at both ends of the track. Test wires are located beyond the second marker by a distance compatible with a power profile of a climb of 15 meters in 7 seconds. Upon crossing the first marker active scan commences and data/display information is recorded. Upon crossing the second marker the pilot begins an avoidance maneuver.

The pilot does not fly by WOWS in this test phase but keeps the aircraft in a straight line track run.

When a wire is detected in any portion of a scan at time t_O the "alert" will be indicated to the observer/WOWS operator by a light and a headset audio warning. Provisions have been included to make the audio warning signal available for the pilot. The display will appear at time $t_O + t_D$ where t_D is a computer controlled delay with a maximum time of 1.5 seconds. The display will include the symbolic indication of the wire in the field of view including "range to the target wire" at time $t_O + t_D$. Other parameters such as initial range, gate pulse time, etc. will be inserted at the operator terminal. These outputs can be simultaneously recorded at the discretion of the operator. However, the video recorder is not included in the WOWS itself.

2.1.2 Effects Of Helicopter Motion

During the airborne tests the pilot is required to maintain a relatively stable flight direction and altitude. Line-of-sight corrections, required because of yaw excursions, will be made via the inertially-stabilized azimuth scan. Corrections required by pitch excursions will be implemented by a non-inertial computer correction arrangement. Roll is assumed to be negligible during the 1.5 seconds of active scan in each frame. It is also assumed that the helicopter altitude will not change appreciably during the test run so that the test wires will remain within the field of view of the system.

An important parameter for system analysis is the forward velocity of the helicopter. The effect of speed is to reduce the probability of detection of a wire and to lower the time allowed for observation/verification between the time of the first warning and the time when an avoidance maneuver is necessary.

2.1.2.1. Coverage Analysis

a) Geometric Coverage

The result of forward helicopter motion is that the laser pulse, during the frame time, sweeps out an arc in terms of ground coverage. Depending upon the forward speed, the scanned FOV, total frame time, and laser pulse width, the coverage geometry may take several shapes which correspond to either total or partial coverage. For any point in the FOV the geometric coverage factor, G, can be estimated by the following expression:

$$G = \frac{\text{Pulse Depth in Forward Direction Total}}{\text{Total Forward Motion During Frame Total}} \times \frac{\text{Scan Time}}{\text{Frame Time}}$$

$$G = \frac{(c\Delta t)}{VT_F} \times \frac{T_s}{T_F}$$

G = Speed of light (m/sec)

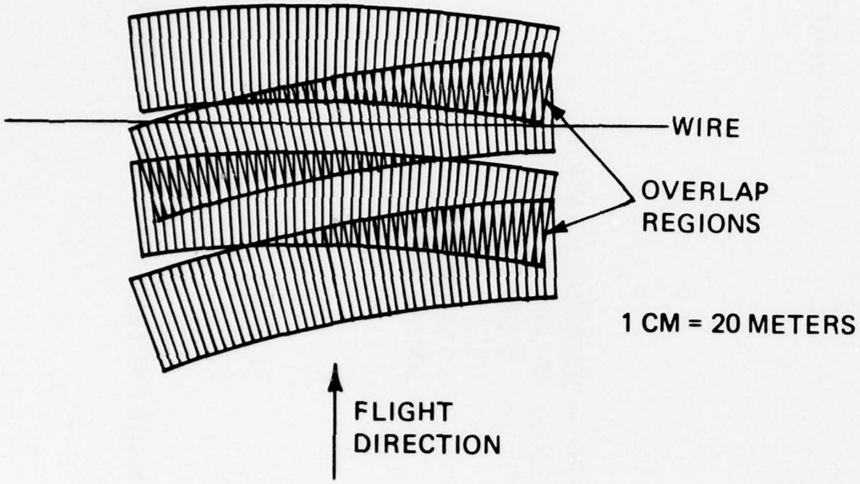
Δt = Pulse duration (sec)

V = Forward velocity (m/sec)

T_s = Active scan time

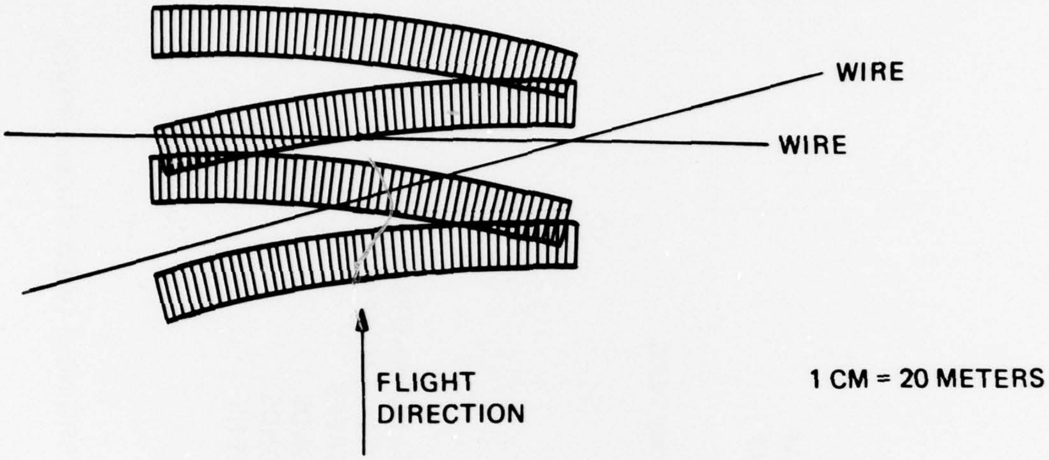
T_F = Total frame time

The geometric coverage pattern is shown in Figure 2-1 for the case where the forward speed is 20 knots and the pulse duration is 100nsec. The figure represents the ground swath covered during 5 consecutive frames as seen from above. A single scan takes place in 1.5 sec; 0.5 sec is allocated for "turnaround" and the scan is repeated in the opposite direction. This figure shows that there are essentially no gaps in coverage so that all wire segments in one field of view will be detected even at the extreme edges. This coverage can be compared with Figure 2-2 where the laser pulse is shortened from 100 to 50 nsec. For this coverage pattern wire segments are not detectable while they are in the gap regions. However, for the given range and total FOV, it is assumed



- FORWARD SPEED = 10M/SEC; 19.5 KNOTS
- PULSE DURATION = 100 NSEC (±15 METERS)
- AZIMUTH SCAN = ±15 DEGREES
- SCAN TIME = 1.5 SECONDS
- FRAME TIME = 2.0 SECONDS
- RANGE = 300 METERS

FIGURE 2-1. GEOMETRIC COVERAGE PATTERN NO. 1 (VIEW FROM ABOVE)



- FORWARD SPEED = 10M/SEC; 19.5 KNOTS
- PULSE DURATION = 50 NSEC (±7.5 METERS)
- AZIMUTH SCAN = ±15 DEGREES
- SCAN TIME = 1.5 SECONDS
- FRAME TIME = 2.0 SECONDS
- RANGE = 300 METERS

FIGURE 2-2. GEOMETRIC COVERAGE PATTERN NO. 2 (VIEW FROM ABOVE) that the wire extends beyond the FOV and will therefore be detected at some point within the displayed scan. A wire that appears across the system field of view will be recognized when only 1/32 of its length is exposed to the detector coverage pattern. This "decision" element size is based on 10 consecutive wire "hits" to establish the recognition decision[4]. It is seen, therefore, that tradeoffs can be made between forward speed, pulse duration, frame time and scan time to establish coverage requirements. The tradeoffs will be characterized during field testing.

2.1.2.2 Flight Reaction Time

It is of interest to determine the various time scales to be expected in a flight test. Specifically, the closing time to obstacle and the minimum pilot reaction time are a function of the air speed and the range discrimination.

Required reaction time can be defined as follows:

$$ta = tc-ts-te$$

where:

ta = reaction time

tc = closing time

ts = scan time

te = evasion time

---

[4] Kleider, A., "Applications of a Charge Coupled Device Sensor for Nap-of-The-Earth Helicopter Operations," AGARD Symp., Ottawa, Canada, Oct. 1977.

The closing time can be expressed as a function of the radar range, range resolution, and helicopter speed as follows:

$$tc = \frac{(R - \frac{\Delta R}{2})}{X \times k}$$

with:

R = preset range to obstacle (m)
ΔR = preset range resolution ($c\Delta t$), (m)
S = helicopter speed (knots)
k = conversion constant (.514 m/sec)

The reaction time can be estimated for specific situations if values are assumed for ts and te.

"ts" is the time from first reception of wire return plus time to process and verify continuity and to execute alarm or display. This total time is in the order of several tenths of a second and can be ignored in this calculation.

"te" is the evasion time it takes for the pilot to climb 15 meters from a straight line flight (in a benign environment). The time estimated for this maneuver is 7 seconds and is consistent with the UH-1 power profile.

During the reaction time the operator may make observations of the display. At the end of this time the pilot must execute the evasive maneuver. Table 2-1 shows the range of reaction time for various helicopter speeds and range discriminations. The table shows that reaction times are small at high speeds. For an experimental system, testing against minimum wires and at the best available range resolution, the tests should be performed at low speed with a preset range of 300 meters.

TABLE 2-1 REACTION TIME

(Range = 300 meters)

Helicopter Speed (Knots)	Reaction Time (sec) at ΔR = 15 meters	Reaction Time (sec) at ΔR = 30 meters
10	50.0	48.4
20	21.4	20.7
45	5.6	5.3
60	2.4	2.2

It is recommended that the initial flight tests be performed over a precalculated range with markers to terminate the data-taking portion of the flight.

2.2 STABILIZATION REQUIREMENTS

Stabilization of the WOWS system is required for two reasons, i.e., to maintain the absolute pointing accuracy of the WOWS in order to meet the required wire location accuracy of .5° with respect to inertial space and to correct for motion effects which are large enough to compromise wire detection. The first requirement, by its nature, implies the need for an inertially stabilized platform.

Therefore, the planned WOWS configuration is based upon an inertially stabilized azimuth scan with a computer correction for elevation excursions. The absolute accuracy with respect to an operator-set flight line will be within the accuracy requirements for level flight conditions. Under more severe maneuvers the absolute wire accuracy may be compromised but wire detection will be preserved.

The WOWS sensitivity to input motions has been discussed previously[5] but is reexamined here. The WOWS is a sampling system capable of pattern recognition. The 30° horizontal FOV is sampled 320 times at 213 samples per second with a vertical line sensor subtending 9° x .01° and comprised of approximately 500 elements. Each successive line is separated in space by up to ten elements. The sample pulse width is 50 to 100 nanoseconds. The output of each sampled line is processed so that only single element responses, such as those

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[5] Kleehammer, op.cit.

produced by wires or noise, are transmitted. The computerized algorithm connects the single site activated bits in a procedure to define lines. Ten aligned bits, or eight with a maximum of two dropouts, designate a wire. This decision is made in .93° of rotation, equal to 1/20 second. Since the system is strobed, each entire line of information is sampled instantly, i.e., no motion occurs between pixels of a given line.

The primary motion factors therefore, are those that occur between the sampled lines and only those whose magnitude is great enough to effect the computer algorithm.

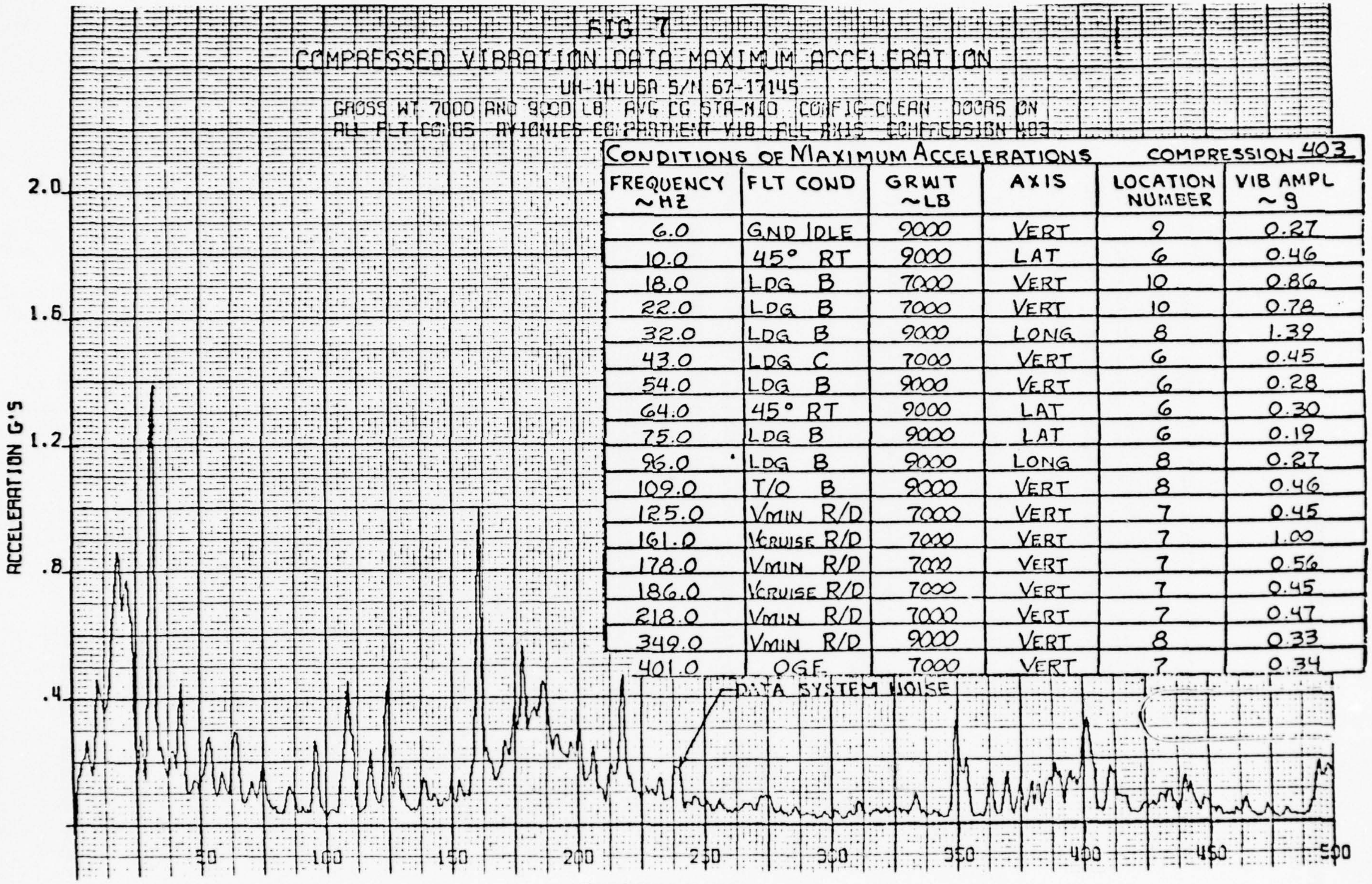
The two sources of helicopter motion are related to vibration and flight line-of-sight (LOS) stability. These sources of potential error are examined in the following paragraphs.

2.2.1 WOWS Vibration Environment

Vibration in a helicopter may be generated by a number of sources. In general, the principal source of vibration in helicopters is the slight imbalance in rotor blades which is transmitted. to the fuselage. Other vibration sources are in the engine(s) and irregular air currents which, through the flexibility of the helicopter frame and various resonances, set up vibrations.

The recorded vibration data on maximum accelerations of the UH-1A helicopter describes the environment for avionics equipment located in the compartments where measurements were taken. This data is shown in Figure 2-3. It is possible to make some assumptions and obtain order of magnitude estimates related to the expected environment of a WOWS system mounted on the chin of the helicopter. This type of analysis, however, cannot be substituted for measurements taken with angular rate sensors in the proper location.

Source: "Vibration and Temperature Survey Production U-H1 Helicopter"
Final Report; U.S. Army Test Activity, Edwards AFB, Calif. Jan. 1973



CONDITIONS OF MAXIMUM ACCELERATIONS COMPRESSION 403

FREQUENCY ~HZ	FLT COND	GRWT ~LB	AXIS	LOCATION NUMBER	VIB AMPL ~g
6.0	GND IDLE	9000	VERT	9	0.27
10.0	45° RT	9000	LAT	6	0.46
18.0	LDG B	7000	VERT	10	0.86
22.0	LDG B	7000	VERT	10	0.78
32.0	LDG B	9000	LONG	8	1.39
43.0	LDG C	7000	VERT	6	0.45
54.0	LDG B	9000	VERT	6	0.28
64.0	45° RT	9000	LAT	6	0.30
75.0	LDG B	9000	LAT	6	0.19
96.0	LDG B	9000	LONG	8	0.27
109.0	T/O B	9000	VERT	8	0.46
125.0	VMIN R/D	7000	VERT	7	0.45
161.0	VCRUISE R/D	7000	VERT	7	1.00
178.0	VMIN R/D	7000	VERT	7	0.56
186.0	VCRUISE R/D	7000	VERT	7	0.45
218.0	VMIN R/D	7000	VERT	7	0.47
349.0	VMIN R/D	9000	VERT	8	0.33
401.0	OGE	7000	VERT	7	0.34

FIGURE 2- 3 U-H1 VIBRATION DATA

An operating helicopter experiences both linear and angular vibrations from the movements of the rotors and the surrounding air. Due to the type of sensor used, only linear motions have been recorded as acceleration. For this data to be pertinent to the stabilization requirement for WOWS line-of-sight, they are converted to angular displacements. Converting the measured data from g's, or acceleration, to translation distance is accomplished by:

$$a = \frac{A\,g}{(2\pi f)^2}$$

where

a = amplitude (feet)
A = acceleration
g = force of gravity (32.2 feet/sec^2)
f = frequency

Solving this equation for 6.0 Hz where the recorded maximum acceleration is 0.27 g gives:

$$a = \frac{.27\ (32.2)}{(2\pi 6)^2} = .006 \text{ feet}$$

If sinusoidal motion is assumed, the full translation is 2 x a or .012 feet = .144 inches.

Applying the same formula to each of the recorded points, the following data is obtained:

Frequency (H_z)	Vib. Ampl. (g)	Double Amplitude (Inches)
6.0	0.27	.144
10.0	0.46	.090
18.0	0.86	.052
22.0	0.78	.031
32.0	1.39	.026
43.0	0.45	.005
54.0	0.28	.002

Frequency (H_z)	Vib. Ampl. (g)	Double Amplitude (Inches)
64.0	0.30	.001
75.0	0.19	<.001
96.0	0.27	<.001
109.0	0.46	<.001
125.0	0.45	<.001
161.0	1.00	<.001

In order to convert displacement into rotation estimates it is assumed that all rotation occurs about the helicopter hub located approximately 115 inches from the scanner. A 6Hz frequency corresponds to a double amplitude of .144 inches. Solving the 2 tangent^{-1} of $(\frac{.144}{2} / 115)$ results in an angle of .07° which at 6 Hz, is equal to 6.3 pixels. Computed motion for other datum points of consequence are:

Frequency (Hz)	Angular Motion	No. Pixels
6	.07 °	6.3
10	.045°	4.0
18	.025°	2.2
22	.015°	1.3
43	.0025°	.2

These angular displacements are computed for an uncompensated sensor hardmounted to the helicopter at the nose chin. The planned platform design approach will incorporate an isolation mounting structure with a resonant frequency below 6 Hz. All angular motions above 6 Hz will, therefore, be attenuated with increasing attenuation as a function of frequency. The angular motion at 6 Hz will become the dominant vibration component with a maximum displacement somewhat less than 6.3 pixels. The actual attenuation will be determined during the system design phase.

The period associated with a 6 Hz displacement is 83.3 msec. The average time over which the displacement accumulates 1/2 pixel is:

$$\left(\frac{.5}{6.3}\right) \text{ X } 83.3 \text{ msec} = 6.6 \text{ msec}$$

Because the interpulse period is 4.68 msec (1.5 sec/320 pulses) the correction is required approximately every pulse to compensate for vibration. Vibration, however, will have a zero mean value so that location accuracy over the entire frame will not be affected.

A unique feature of the WOWS is that the computer algorithm is only sensitive to the component of vibration in the pitch axis. The one-dimensional nature of the wire results in relative immunity to vibration in the azimuth direction.

2.2.2 Flight Test Data

AVRADCOM has supplied a data record of an actual UH-1 nap-of-the-earth flight at Mullica River, New Jersey. This data has been analyzed to determine the optimum WOWS configuration and the expected LOS stability. The data consisted of 124 pages of computer printout containing the heading, pitch, roll and flight time. The resolution on all angles was .01 degrees; the resolution in time was 0.1 second. Airspeed was not given.

Inspection of the record showed widely varying situations where the heading, pitch, and roll were all changing independently, apparently due to maneuvers. However, there were portions of the record that appear to be straight line portions of flight as would be expected during WOWS helicopter testing. A portion of the data was analyzed to clarify what may be expected from an actual NOE flight environment.

The procedure used was as follows:

> A portion of the data record was located where the heading was relatively constant. The maximum and minimum values in all three angle readouts were located. The difference between the maximum and minimum values found in any axis was defined as the maximum excursion in the axis.

Table 2-2 displays a summary of the results for three such records. The maximum excursion rate took place only over a time duration of several seconds. For the straight line flight, the heading and pitch excursions were all less than 0.64 deg/sec. In the same records, the roll excursion was 0.83 deg/sec and 2.44 deg/sec. The conclusion derived is that the roll, pitch and heading values are within a range where computer stabilization can be effective.

These data excerpts appear to be from relatively quiet portions of the flight where straight line track was executed (and apparently altitude was constant). It is expected that WOWS flight testing will be executed with similar conditions.

These data also confirm previous estimates made by Bell Helicopter, i.e., that controlled flight does not exceed two degrees in two seconds in any axis over short durations.

The maximum range of angles encountered during the mission has been noted. The heading, or course, varies over a full 360 degrees. The range of pitch and roll is as follows:

Pitch:	+12/8 deg.	to	-7.8 deg.
Roll:	+48.5 deg.	to	-40.3 deg.

These ranges are noted in order to properly protect the WOWS Scanner during all non-active flight periods where maneuvers are necessary.

TABLE 2-2 MULLICA RIVER FLIGHT/UH-1

Conditions:

- 12.4 minutes total duration
- Readout resolution = 0.01 deg.
- Sample Rate: 10Hz
- NOE flight

Excerpts From Data

Record 1, Excerpt = 2 sec. (48.120 to 48.140)

		DURATION
Peak Heading Excursion:	0.35 deg/sec	(1.4 sec)
Peak Pitch Excursion:	.45 deg/sec	(2.0 sec)
Peak Roll Excursion:	2.44 deg/sec	(1.4 sec)

Record 2, Excerpt = 6 sec. (42.583 to 43.43)

Peak Heading Excursion:	0.46 deg/sec	(3.6 sec)
Peak Pitch Excursion:	0.64 deg/sec	(3.9 sec)
Peak Roll Excursions:	0.93 deg/sec	(2.7 sec)

Banking Flight

Record 3, Total Duration = 28 Seconds

Heading uniform banking rate = 6.42 deg/sec over 28 seconds
(complete 180 deg turn)

Peak Pitch Excursion: 0.34 deg/sec over 19.4 sec.

Peak Roll Excursion: 6.86 deg/sec over 5.4 sec.

2.2.3 Pitch Correction

The discrete addressability of the CCD sensor provides an inertia-free method of correcting pitch motion from any source including vibration and LOS flight stability. If the amount of pitch undergone by the sensor, from one sample line to the next, is measured and scaled to equal the number of pixels of image shift, then this count of ± X pixels can be algebraically added to the addresses of the detected wire position in the second line. This scheme prevents the algorithim from failing in a displaced line sample and preserves the geometric accuracy in the vertical axis relative to the frame start position. This concept can be implemented using an absolute pitch position encoder, a pitch rate sensor, or a pitch accelerometer whose output is integrated.

In order to determine the maximum amount of pitch rotation from one line sample to the next, the definite integral of velocity is evaluated from $\pi-(2\pi f \frac{4.69\text{ms}}{2})$ to $\pi+(2\pi f \frac{4.69\text{ms}}{2})$. That is, the position sinusoid is sampled around the zero point to find the maximum rotation possible between samples.

To instrument this correction a circuit similar to that shown in block form in Figure 2-4 will be used. The pitch accelerometer is integrated to yield velocity. Velocity, sampled every 4.69 msec, yields motion in radians. Velocity changes between line samples are integrated (smoothed) in the sample and hold circuit to yield an average value. The scaling operational amplifier adjusts the velocity value so that one pixel of rotation produces one increment in the third least significant bit of the A/D. The six most significant bits, therefore, become a precise count of pixel shift over a range of ± 64 pixels/line. An offset is

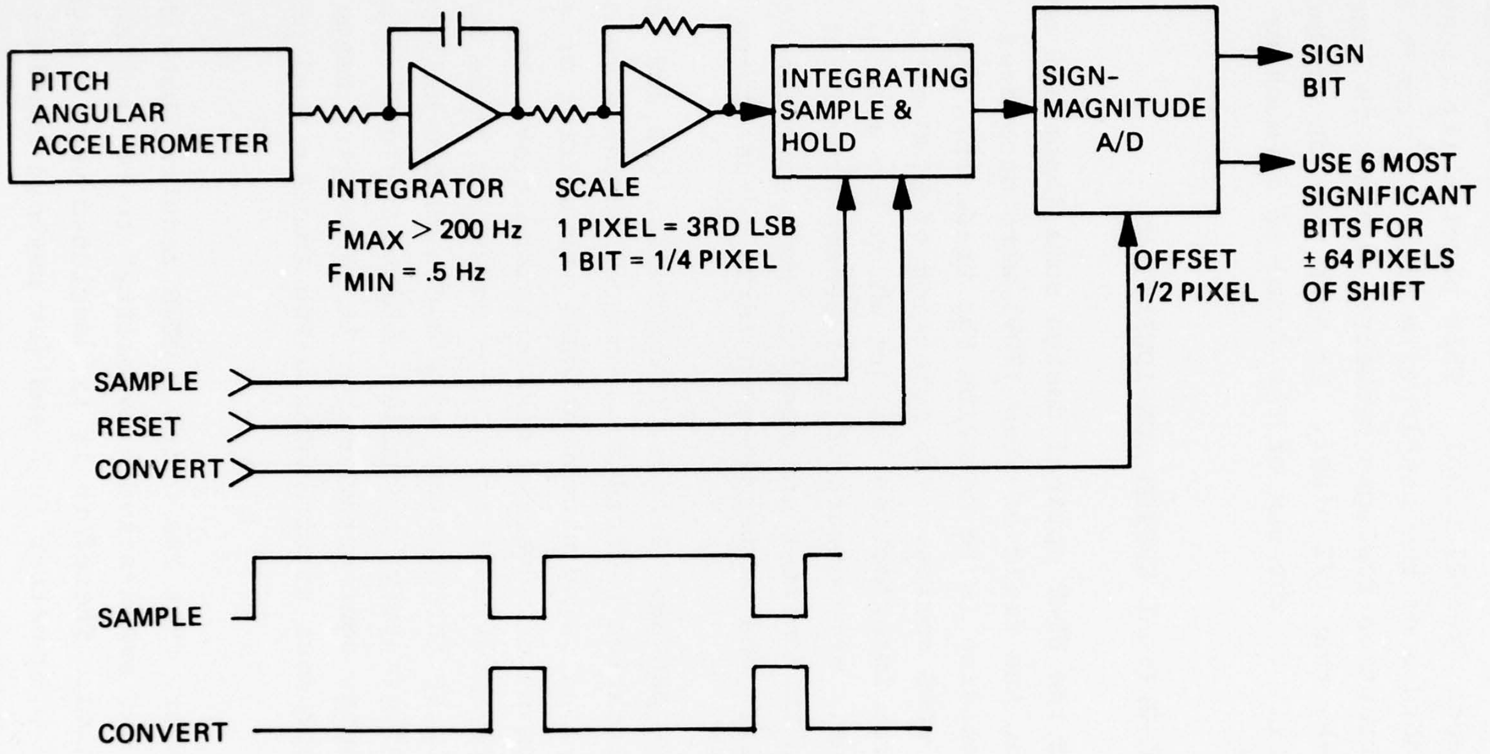


FIGURE 2-4. CORRECTION CIRCUIT

79-008

used to adjust the A/D so that pixel shifts are made whenever the rotation exceeds (X+1/2) pixel. This pixel shift count is applied to the address of the single site hits to correct for motion. This correction realigns geometry unless each line-to-line change is less than 1/2 pixel. In this case an accumulated vertical image shift at the end of the frame of as much as 160 pixels can result.

2.3 ELECTRO-OPTICAL DESIGN CONSIDERATIONS

During studies of the WOWS optical design some important consequences of scaling the field-of-view (FOV) were uncovered. The purpose of this section is to describe the trade-offs required to establish the WOWS optics. The selection of WOWS optics was affected by several interlocking factors which are specialized to the application. All-refractive type lenses are planned for use in a separate transmitter and receiver configuration because the approach offers good performance in terms of detection range.

The overall optics package (lenses, intensifier, CCD and laser) for the WOWS application reduced to a choice between a relatively large optical payload using a conventional intensifier or a smaller payload using an advanced design intensifier. The large payload can readily provide the required detection range but the package size would be inconsistent with a desireable helicopter configuration. Alternately, a smaller optical payload results in a suitable helicopter configuration but its detection range performance can not meet requirements using conventional production intensifiers.

It is clear, however, that the overall WOWS requires both detection range capability and small-sized "flyability" to be suitable for the WOWS application. Therefore it is concluded that a high-sensitivity image intensifier in a smaller payload configuration will be needed to satisfy program requirements and goals.

2.3.1 Electro-Optical Configuration

The field of view, FOV, of a general optical system is defined as the ratio of the image plane dimension p, to the effective focal length, f. For the WOWS optics:

$$\theta_v = \frac{p}{f}$$

where

θ_v = optical FOV
p = image plane dimension (m)
f = effective focal length (m)

The precise value of the image plane dimension is a characteristic of the optics type and of the criteria used to define the usefulness of the image quality. In order to compare different optical systems, consider that the optics are suitable for imaging at a spatial frequency of 12.5 lp/mm which corresponds to 1000 CCD elements across a 40mm image intensifier. At this spatial frequency the optical MTF must be high, e.g., 0.90. The extent of optical FOV, the transmission, the f/number, the focal length, the image dimension, and the degree of optical correction determines the size, weight and degree of difficulty of the optics design. For WOWS, the f/number of the receiver should be maintained as small as possible.

2.3.1.1 WOWS Transmitter

For the transmitter, the f/number is determined by the value required to capture 90% of the energy contained in the 18 degree laser beam (in both directions).

The f/number and full cone angle, are related as follows:

$$\underset{\text{(in air)}}{\text{f/number}} = \frac{1}{2\sin\left(\frac{\Theta}{2}\right)}$$

For the WOWS transmitter the required f/number is 3.2. Further lowering of the f/number will make the optics more complex but will not result in the collection of much more energy because of the approximate Gaussian profile of the laser pattern. In order to prevent excessive loss of energy out of the FOV, near the edges of the FOV, the aperture diameter should be increased beyond that required by the geometric f/number. This size increase is estimated to increase the weight by 10-20%.

A review of lens types, as well as specific patents, was made for the transmitter. A telephoto type was selected as the lowest risk design approach suitable for a 9 degree FOV and a 0.2 mrad IFOV. No lens was found that could be described as "off-the-shelf". For the selected approach a computer program (ACOS 5), based upon a patent prescription, was run. The results showed that the performance was excellent on-axis but further design effort is required to improve the performance off-axis and specific optimization at $\lambda = .85$ is required.

The design of the laser transmitter is complicated by the laser "integrator" which is required to smooth the hot spots that occur along the linear extent of the laser diode array. Without the presence of an integrator the laser output, focused at 300 meters, would consist of a granular distribution of point sources instead of a uniformly distributed line of output energy. An integrator should consist of a quartz plate with angular dimension of 9 x .0114 degrees, corresponding to physical dimensions of 2" by .004".

From a practical design point of view, the laser integrator can be made with a thickness of .006" but not .004". In this case the laser energy transmitted into a 0.2 mrad beam would only be 2/3 of the actual output power. Therefore, careful attention is needed in the matching of transmitter and receiver FOV's to minimize losses of power.

2.3.1.2 WOWS Receiver

The receiver requirement is based on the need to achieve the lowest T/number possible for use with a suitable image intensifier. The image intensifier diameters available in a fast-gating type are 40mm, 25mm, and 18mm. Because it is somewhat arbitrary which intensifier format is placed at the focal plane, it is important to distinguish the optical FOV with the useful detector FOV, θv, given by

$$\theta v = \frac{d}{f}$$

where

d = image intensifier dimension
f = focal length

For example, consider that a receiver is designed for use with a 40mm image intensifier and is corrected for this dimension. If the focal length is chosen to yield a 9 degree optical FOV, the useful FOV for the 40mm intensifier will also be 9 degrees. However, if the intensifier is replaced with a 25mm or 18mm type, the useful detector FOV will decrease to 5.6 and 4.0 degrees, respectively. The size and weight of the optics, therefore, is still determined by the image plane FOV.

The following table shows the relation between the focal length and FOV for the different scaling approaches that can be used for WOWS.

INTENSIFIER FORMAT	FOCAL LENGTH SCALED		FOV SCALED	
	OPTICAL FOV		FOCAL LENGTH	
	12 DEG.	8 DEG.	7.5"	4.5"
40mm	7.5"	11.2"	12 deg.	20 deg.
25mm	4.7"	7.2"	7.5 deg.	12.5 deg.
18mm	3.4"	5"	5.4 deg.	9 deg.

(a) MTF Considerations

The proper figure-of-merit for the optical coupling of the receiver is the factor of encircled energy, w. This factor expresses the ratio of the total energy incident on the receiver to the energy collected by the CCD pixel in the geometrical instanteneous FOV. A numerical technique has been derived to determine this factor when the shape of the overall MTF is known. The overall MTF is obtained by cascading the MTF's of the optics, image intensifier, and CCD components. The major limiting MTF factor is related to the image intensifier. An approximate method for defining the factor of encircled energy is that it is numerically equal to the square root of the overall MTF. For example, if the MTF is equal to 0.24, as is typical of a 40mm format at 12.5 lp/mm, the value of w is equal to 0.5. Therefore, only one-half of the laser return will be detected in this example. As a practical matter the image intensifier MTF changes with format due to the variability of high resolution microchannel plates. The smaller the intensifier format the lower the intensifier MTF. At 12.5 lp/mm typical MTF values for the 40mm, 25mm, and 18mm intensifiers are 0.27, 0.4, and 0.54, respectively, due to fabrication with different microchannel plate sizes.

Also, the spatial frequency of operation is dependent on the number of CCD pixels used and the fiber optic minification used to couple the output phosphor to the CCD. The maximum possible minification is given by

$$M = \frac{\text{(image intensifier format)}}{\text{(CCD length)}} \qquad \text{(for } M \geq 1\text{)}$$

The spatial frequency of operation at the photocathode is given by:

$$SF = \frac{\text{(\# of CCD Elements)}}{(2)\ \text{(Image intensifier format)} \times (M)}$$

Table 2-3 shows the calculated performance of the detector based upon the use of 1024 resolution elements. For this case, the 40mm intensifier performs best but can only collect about 50% of the laser energy. Use of smaller formats degrades the factor of encircled energy further.

Table 2-4 shows the calculated performance for the case where detector performance is based upon optimizing performance at a fixed optical MTF. The factor of encircled energy can then be increased at the expense of the number of pixels (and instantaneous FOV).

(b) Coupling Efficiency

For the detector, as described, the instantaneous receiver FOV,

TABLE 2-3 DETECTOR PERFORMANCE BASED UPON 1024 RESOLUTION ELEMENTS

INTENSIFIER FORMAT	MAXIMUM MINIFICATION	SPATIAL FREQUENCY AT PHOTOCATHODE (lp/mm)	W
40mm	3 to 1	12.8	.50
25mm	1.87 to 1	20.5	.44
18mm	1.35 to 1	28.4	.40

ASSUMPTIONS:

- 1024-Element CCD
- 13µm pixel size center-to-center
- Based upon available microchannel intensifiers

TABLE 2-4 DETECTOR PERFORMANCE BASED UPON FIXED SPATIAL FREQUENCY AT PHOTOCATHODE

INTENSIFIER FORMAT	MINIFICATION	# OF PIXELS	W
40mm	3 to 1	1024	.5
25mm	3 to 1	640	.60
18mm	3 to 1	460	.72

ASSUMPTIONS:
- 1024-Element CCD
- Based upon available microchannel intensifiers

$\Delta\Theta_R$, can be written

$$\Delta\Theta_R = \frac{\text{pixel size at photocathode}}{\text{receiver focal length}}$$

$$= \frac{\text{(image intensifier format)}}{\text{(minification) (\#pixels) (Receiver focal length)}}$$

When scaling the focal length, the ratio of the instantaneous FOV of the receiver to the transmitter determines the coupling efficiency of the combination. If this ratio is less than unity, a further loss of efficiency is incurred which is important in the overall detection range equation. When the ratio is greater than unity all the available transmitted energy is collected.

Including the expression for the transmitter, the coupling efficiency is given by

$$k = \frac{d\ f_t}{N.f_R.t}$$

where

d = image intensifier format (mm)
f_t= transmitter focal length (mm)
f_R= receiver focal length (mm)
N = # of pixels
t = laser integrator thickness (mm)

For the proposed sensor

$$k = \frac{(40\text{mm})\quad(19")}{(1024)\ (7.5")\ (.152\text{mm})} = 0.65$$

and only 65% of the energy of the laser is subtended by the receiver. The overall collection efficiency is given by the product of the factor of encircled energy and the coupling efficiency and is equal to 0.32 (neglecting optical transmission or the effect of f/numbers). Therefore, extreme care is necessary with regard to collection efficiencies and MTF effects in scaling the optics.

(c) Gating Considerations

A further loss of power may be incurred due to the finite response of the image intensifier. The risetime of each format intensifier is different and is given below,

Format	Risetime	Pulse width*
40mm	20 to 50nsec	40 to 100 nsec
25mm	≤15nsec	≤30nsec
18mm	≤5nsec	≤10nsec

*at about 50% power

The half power pulse width is estimated by assuming that the pulse shape is trapazoidal. The result is that the smaller format intensifiers exhibit faster response times.

2.3.2 Predicted System Performance

The factors defined in the previous discussion can be combined in a way that illuminates the WOWS system performance, i.e., plotting the achievable detection range, Ro, as a function of optical payload weight. The detection range is calculated from the range equation as previously derived and shown in Table 2-6.

The payload weight, W_T in lbs, is estimated by scaling the optics weight as the cube of the focal length ratio. For the transmitter

$$W_T = W_{TO}\left(\frac{F_T}{19''}\right)^3$$

Where

W_{TO} = estimated weight of proposal optics (glassware & casing)

F_T = new transmitter focal length

The value, W_{TO}, is based upon a 7-8 element, f/3.2, telephoto type lens.

TABLE 2-6 RANGE EQUATION

$$Ro^3 e^{-2\alpha Ro} = \frac{kREL\ T_T\ (Tw)^2\ W\ d^2}{4e\ N_t\ (T/\#)^2} \cdot \frac{r_t\ D}{(\theta v)^3}$$

Factor	Definition	Value
Ro	Detection Range	See Figure 2-5
α	Extinction Coeff	$.16\ (km)^{-1}$
k	Coupling Efficiency	*
R	Photocathode Responsivity	
	Present	.01 A/W atλ= .85μm
	Future	.14 A/W atλ= .85μm
E	Laser Output Flux	$.3 \times 10^{-3}$ J/Pulse.m(λ=.85)
L	Laser Length	*
T_T	Transmitter Transmission	.9
T_w	Window Transmission - two way	$(.98)^2$
W	Factor of Encircled Energy	*
d	Image Format	*
e	Coul/Electron	1.6×10^{-19}
N_t	Target Electrons	16
T/#	Receiver T/#	1.05
r_t	Target Reflectivity	.25
D	Wire Diameter	3×10^{-3}m
θv	Total Vertical FOV of Detector	*

* Varies for each point on curves in Figure 2-5

Notes:

1) Range Equation assumes that image intensifier format is matched to FOV of Receiver.

$$\theta v = \frac{d}{f_R}$$

2) $k = \Delta\theta_R / \Delta\theta_T$

3) No loss of power due to gating risetime/falltime

The overall payload weight, W_S, is estimated as follows:

$$W_S = 10 \text{ lbs} + 1.1 (W_R + W_T)$$

where the initial value of 10 lbs includes the laser, image intensifier/CCD/FO, preamp card, and associated mounting structure.

The coefficient, 1.1, is based on the reasoning that the outside mounting and support will grow as the optics weight increases and may be 10% of the optics weight.

Figure 2-5 summarizes the results of this trade-off for the approach where the image plane of the optics is intended for both a 40mm and a 18mm format. Because of the cubic relation in focal length, the effect of increasing image plane FOV (smaller focal length) is dramatic in terms of system weight.

An advantage of the smaller FOV is that the laser array length can be shortened to fit the smaller FOV. If a 18mm intensifier is used at the 40mm image plane, the laser array can be reduced from 4.0" to 2.0" in length.

Consider a WOWS system based upon a 9 degree useful FOV and a 18mm intensifier. The vertical IFOV would be 0.33 mrad which is slightly larger than the desired value of 0.2mrad. The number of pixels would be 460. The lower payload weight of this configuration would permit building the WOWS in a lighter weight flyable helicopter configuration than the configuration where 40mm intensifier and larger focal length optics would be used.

Therefore, after consideration of the various elements of the program including the optics, the gatability of the intensifier, the laser development, the mechanical realization of the helicopter

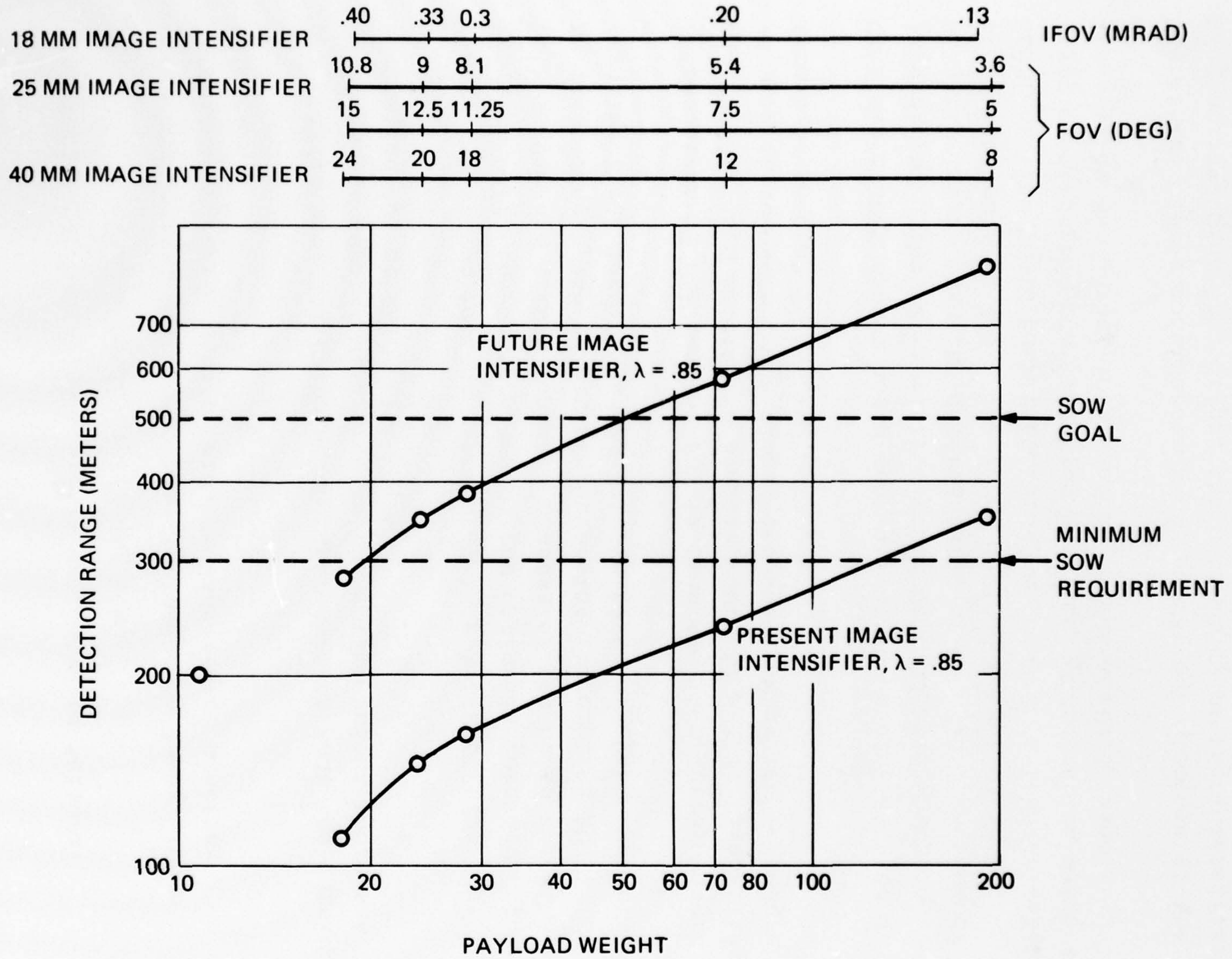


FIGURE 2-5. WOWS RANGE VERSUS WEIGHT

mounting it is concluded that it is desireable to proceed with the smaller, lightweight payload which is consistent with a flyable development model.

APPENDIX A

LASER SAFETY

The GaAlAs Laser planned for use with the Wire Obstacle Warning System (WOWS), has been evaluated with respect to personnel safety and is a Class III Laser. This type of laser is characteristically a potential hazard if directly viewed by an unprotected eye, but does not (unless focused) cause hazardous reflections.

This appendix section contains calculations to establish actual irradiance levels and protection criteria for operating of such a laser.

It is shown that the actual output of the laser is a serious threat if directly viewed. Therefore, safety recommendations are made for testing and alignment procedures.

Furthermore, it is shown that operation of the laser with the beam-forming optics in place is not a serious hazard and can be treated in a more routine way.

LASER SAFETY STANDARD CALCULATIONS

REFERENCE: TB MED 279
"Control Of Hazards To Health From Laser Radiation"
18 September 1974

According to the laser hazard classification, the WOWS GaAlAs laser array is a Class III, medium power laser device. It can emit a radiant energy in excess of Q exempt but cannot emit a radiant exposure that exceeds that required to produce a hazardous diffuse reflection as given in attached Table A-4 excerpted from the reference document.

The GaAlAs laser has an operating wavelength of 0.85μm. According to Figure A-1 from the reference document the correction standard factor $C_A = 2$ at this wavelength.

ESTABLISHMENT OF PROTECTION CRITERIA

a. Direct View

Using Table A-1 the appropriate protection standard, P, for direct view of the source is given as:

$$P_{\substack{eye \\ Direct}} = 0.5\ C_A\ \mu J/cm^2$$

For a defining aperture of 7mm and 1 nsec to 18 nsec pulse width.

Therefore we have:

$$P = \frac{2}{2}\ \mu J/cm^2 = 1 \mu J/cm^2$$

b. Reflected View for a Single Pulse

Similarly, the eye protection standard for irradiance by a diffuse reflector is:

$$P_{\substack{eye \\ diffuse}} = 10 \Pi C_A{}^3 \times (100 \times 10^{-9})\ \ J/cm^2$$

$$= 2.5 \times 10^{-5}\ \ J/cm^2$$

c. Skin Exposure

The skin protection level is found from Table A-3.

$$P_{skin} = 20 J/cm^2 \qquad \text{(single pulse)}$$

These various levels are defined as the absolute maximum exposures which can be incurred in various situations and still be safe.

ESTIMATE OF ACTUAL OUTPUT LEVELS

a. Direct View

For a laser emitting 5.0 kW in 100 nsec and an emission area from the 2" x 6.0 mils integrator, the output radiant intensity is:

$$E_{\text{Eye Direct}} = \frac{5.0 \times 10^{+3}\text{watts} \times 100 \times 10^{-9}\ \text{sec}}{2 \times 6.0 \times 10^{-3} \times (2.54)^2}\ \text{J/cm}^2$$

$$= 6.45 \times 10^{-3}\ \text{J/cm}^2$$

This value is over 6000 times the allowable safety level. Therefore, for direct eyeball observation of the emitting junction, laser safety glass with optical density of 4.0 is required at $\lambda = .85\ \mu\text{m}$. Since the laser radiation is invisible, no purpose is served by direct view of the laser radiation and this activity will be prohibited. Wrap-around goggles will be used. Test installation or alignment of the laser source represents a serious hazard and will be controlled.

The direct view of the output of the laser transmitter is scaled by the area of the transmitter transmission and magnification. An 18 degree divergence laser source at 12" (focal length) effectively fills the aperture. Therefore, the peak irradiance at the exit of the transmitter is

$$E_{\text{Optics}} = \frac{5.0 \times 10^{+3}\text{watts} \times 100 \times 10^{-9}\ \text{sec}}{\frac{\pi}{4}(3.75")^2\ (2.54)^2}$$

$$= 7.0 \times 10^{-6}\ \text{J/cm}^2$$

This level is slightly larger than the protection level so that proper precautions must be taken to prevent personnel from directly looking into the transmitter optics at close ranges.

b. Reflected Exposure

The maximum reflected radiant exposure from a diffuse target of 0.9 at 10 meters is

$$H = (.9)\ \frac{A_T \cdot E_{Optics}}{\Pi\ R^2}$$

For a 1 square ft target,

$$H = \frac{(.9) \times (12 \times 2.54)^2 \times 7.0 \times 10^{-6}}{(3.14) \times (10 \times 100)^2}$$

$$= 1.86\ nJ/cm^2$$

$$(\cos \Theta = 1)$$

This value is an insignificant fraction of the protection level for this type of viewing.

c. Skin Exposure

At the output of the integrator the level of exposure is 3.28×10^{-4} of the level required for skin protection.

SAFETY CONCLUSIONS

- Direct view of the laser array during laboratory operation without appropriate safety goggles is to be avoided. Goggles and /or instrument aided vision will be mandatory for work with the exposed laser source. Instruments such as silicon vidicons and CCD-TV are suitable for alignment operations and to test uniformity and beam pattern. Image converters can also be used.
- During operation, with beam forming lenses in place, no serious hazards are expected. The principle laser hazard control

rests with the operator in avoiding direct aim at mirror like surfaces or potential observers.

- A suitable marked area will be designated for laboratory laser test and operation. Personnel will be designated as required. The laser safety officer will take responsibility for the operation and installation.

- Other hazards, such as electrical, will be eliminated during design of equipment. The installation shall be equipped with a master panel accessible to the laser operator which can turn off all power in an emergency.

- For both ground-based and helicopter-based testing a laser safety interlock key will be provided at the master control panel. Only authorized personnel will be issued keys. The control panel will also have an overide switch to turn off the laser at any time.

TABLE A-1 PROTECTION STANDARDS FOR OCULAR EXPOSURE INTRABEAM VIEWING OF A LASER BEAM SINGLE EXPOSURE

Spectral Region	Wavelength (nm)	Exposure Time (t)	Protection Standard	Defining Aperture (mm)
IR-A	700-1060	1ns to 18μs	$0.5C_A\mu J.cm$	7

TABLE A-2 PROTECTION STANDARDS FOR LASER RADIATION EXPOSURE OF THE EYE VIEWING EXTENDED SOURCES AND DIFFUSE REFLECTIONS

Wavelength (nm)	Exposure Duration	Irradiance	Radiance
700-1060	1ns to 10s	$10\pi C_A{}^3\sqrt{t}J.cm^{-2}$	$10\pi C_A{}^3\sqrt{t}J.cm^{-2}.sr^{-1}$

TABLE A-3 PROTECTION STANDARDS FOR SKIN EXPOSURE TO A LASER BEAM

Spectral Region	Wavelength	Exposure time (t) seconds	Protection Standard
Light & IRA	400nm to 1400nm	10^{-9} to 10^{-7}	2x10 $J.cm^{-2}$

TABLE A-4 MAXIMUM ALLOWABLE RADIANT INTENSITY FROM A DIFFUSE SURFACE REFLECTION AS MEASURED AT THE REFLECTING SURFACE

Duration of Exposure (sec)	Protection Standard at Cornea	Limiting Angle, αmin	Permissable Laser Beam Radiant Exposure		
			P=100%	P=50%	P=10%
10^{-7}	$4.6x10^{-2}$	3.7	$1.5x10^{-1}$	$2.9x10^{-1}$	1.5

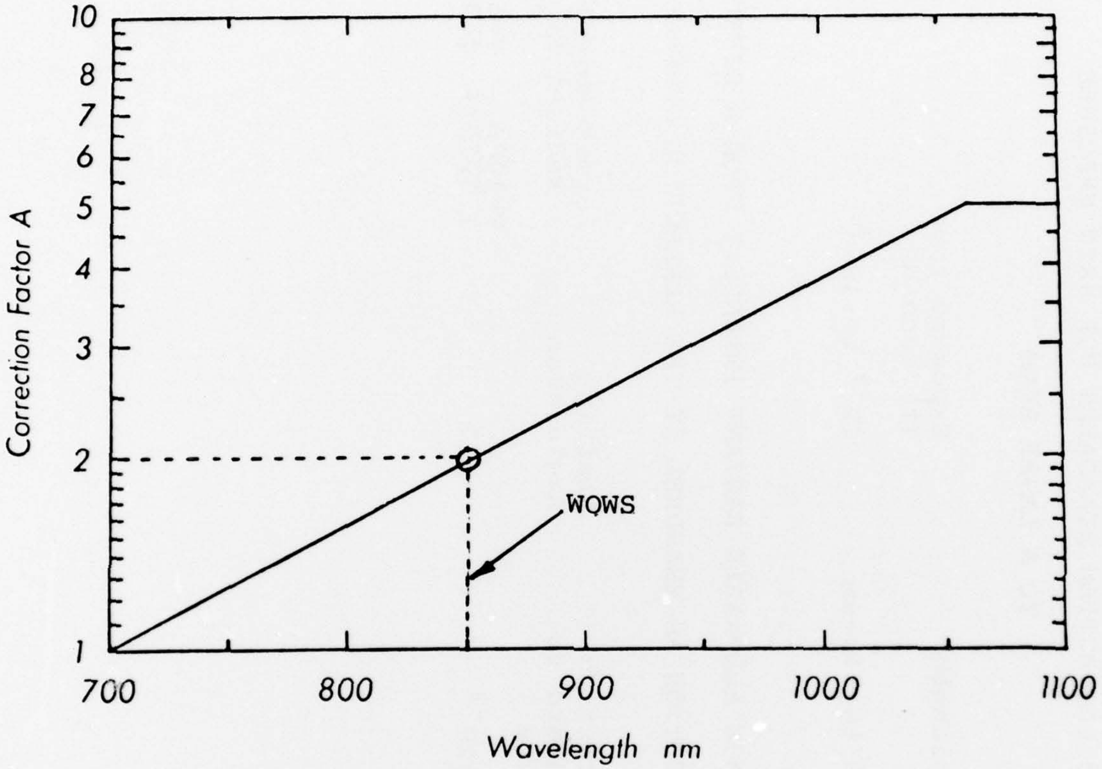


Figure A-1 *Protection standard correction factor (C_A) for laser wavelengths between 700 and 1100 nm. C_A = 5 for wavelengths between 1100 and 1400 nm.*