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Alternatives to Pyrotechnic Distress Signals; Supplemental Report

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Alternatives to Pyrotechnic Distress Signals; Supplemental Report

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16. Abstract (MAXIMUM 200 WORDS) This report is a follow-on to the Coast Guard Research and Development Center Report "Alternatives to Pyrotechnic Distress Signals; Laboratory and Field Studies," which capped a multi-year project effort that developed a specification for a light-emitting diode (LED) signal characteristic as an alternative to pyrotechnic, maritime distress signal flares as <i>visual</i> distress signals. This report describes the steps to determine the characteristic for a near-infrared (IR) component of the two-color visual distress signal so as to provide a night-vision imaging system user a signal, conspicuous against certain lighting conditions, at six nautical miles, in 10 miles meteorological visibility. This report also includes the results of a brief comparison among the ranges of duty cycle for the two-color, visual signal described in "Alternatives to Pyrotechnic Distress Signals; Laboratory and Field Studies."			
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EXECUTIVE SUMMARY

The Coast Guard Research & Development Center (RDC) executed a multi-year project-effort to develop a specification for a light-emitting diode (LED) signal characteristic that could be an alternative to a pyrotechnic, maritime distress signal flare as a *visual* distress signal. Since the project emphasized development of a visual signal, the work specifically avoided evaluating signal characteristics that targeted different types of electronic/electro-optical sensors, including infrared (IR), ultraviolet (UV), or other non-visual sensors.

On completion of the visual-signal work, sources at the Coast Guard's Aviation Logistics Center questioned whether the new visual signal would be detectable to searchers using third-generation, night-vision imaging systems (NVIS), especially those with "minus-blue" filtering (MBF). (Minus-blue filtering is an adaptation which allows NVIS use in situations where aircraft-cockpit lighting might present windscreen-reflectance issues.) As aircraft searches account for approximately 21% of the total search and rescue sorties, the project sponsors (Coast Guard Offices of Design and Engineering Standards, Search and Rescue, and Auxiliary and Boating Safety) concurred with the project team recommendation to investigate NVIS compatibility, and provide a recommended solution.

The first phase of this investigation evaluated whether an individual with NVIS could detect the two-color visual signal. In a laboratory environment (completely dark) the signal was detectable, but in subsequent field trials at an abbreviated distance (2 nautical miles (NM) vice 6 NM), an operator with NVIS could pick out the two-color signal only when the signal intensity was four times greater than that needed for the visual signal to be discernible at 6 NM. This level of intensity would not be practical for an actual device, so the project decided not to try at 6 NM, and moved to investigate near-IR signals.

RDC determined that best results were most likely with LED output closer to the center of the NVIS with minus-blue filter sensitivity curve. Subsequent preliminary testing allowed RDC to develop the specifications for a near-IR signal generator, using 830 nm LEDs at multiple levels of output power.

RDC then conducted subjective evaluations with eight observers using NVIS with MBF. Test team members displayed decreasing levels of near-IR signals from approximately 6 NM, and observers rated how well they could discern the signal against the ambient light "clutter." Experimenters then displayed signals of varied intensities in the range of the initially determined, lowest-discernible output signal. Analysis showed that an 830 nm signal at an output level of 21 milliwatts (mW) per steradian (sr) was the minimum strength for acceptable discernment of the signal.

During the near-IR signal field trial, the RDC project team also conducted a brief subjective trial concerning relative visibility of the two-color visual distress signal, at signal duty cycles different from the initially tested 50% duty cycle. Results indicated that observers found no significant difference among signals that varied from 10% to 50% duty cycle, provided, that the signal's effective intensity remained at or above 50 candela.



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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

cd	Candela
CG	Coast Guard
Hz	Hertz (cycles per second)
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IR	Infrared
K	Kelvin
LED	Light-emitting diode
MBF	Minus-blue filter
ms	Millisecond
mW	Milliwatt
NM	Nautical mile
nm	Nanometer (1×10^{-9} meter)
NVIS	Night-vision imaging system
Pt	Point
PWM	Pulse width modulation
RDC	Research and Development Center
R-Or	Red-orange
SAR	Search and rescue
sec	Seconds
sr	Steradian (SI unit of solid-angular measure)
SOLAS	Safety of Life at Sea
UV	Ultraviolet
V	Volts
VDSD	Visual distress signal device



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1 INTRODUCTION

The Coast Guard (CG) Research & Development Center (RDC) executed a multi-year project-effort to develop a specification for a light-emitting diode (LED) signal characteristic that could be an alternative to a pyrotechnic, maritime distress signal flare as a conspicuous, unique, *visual* distress signal. Since the project emphasized development of a visual signal, the work specifically avoided evaluating signal characteristics that targeted different types of electronic/electro-optical sensors, including infrared (IR), ultraviolet (UV), or other non-visual sensors. The result of this work is a two-color (cyan and red-orange), group alternating flashing signal, and is documented in the March 2015 Report CG-D-04-15, Alternatives to Pyrotechnic Distress Signals; Laboratory and Field Studies (Lewandowski, et al, 2015).

On completion of the visual-signal work, sources at the CG Aviation Logistics Center questioned whether the new visual signal would be detectable to searchers using third-generation, night-vision imaging systems (NVIS), especially those with “minus-blue” filtering (MBF). (Minus-blue filtering is an adaptation which allows NVIS use in situations where aircraft-cockpit lighting might present windscreen-reflectance issues). As aircraft searches account for approximately 21% of the total search and rescue sorties¹, the project sponsors (CG Headquarters Offices of Design and Engineering Standards, Search and Rescue, and Auxiliary and Boating Safety) concurred with the project team recommendation to investigate the NVIS compatibility issue, and provide a recommended solution.

RDC conducted a multi-phased follow-on effort to examine NVIS and the two-color signal, and NVIS with near- IR LEDs, to develop a signal characteristic that when combined with the visual signal, would allow detection by searchers using NVIS with minus-blue filtering.

Though not originally intended as part of the NVIS effort, RDC experimenters used the field trial to also conduct a brief subjective trial concerning relative visibility of the two-color visual distress signal, at different signal duty cycles.

¹ Coast Guard Business Information query for SAR sorties 2005-2014. Query compared “all aircraft SAR sorties,” to “all SAR sorties” (including non-CG resources), but did not identify night-time versus day-time sorties.



2 THE TWO-COLOR ELECTRONIC VISUAL DISTRESS SIGNAL AND SPECTRAL DISTRIBUTION

The two-color electronic visual distress signal device characteristic is a group-alternating, cyan and red-orange flashing LED signal. *Specific-color* LED's emit light in a relatively narrow spectral band when compared to incandescent lights, vapor tubes, or even white LEDs. This concept of a “narrow-band” signal explains why NVIS with a filter that blocks much of the visible-light spectrum will not allow intensification of certain signals. Three approximate spectral-output comparisons help illustrate this. (Note: The depictions in the following images are approximate. For all curves shown, as signal spectral distribution approaches zero, the curve tapers asymptotically, i.e., the curve “approaches” zero where indicated, but actually extends farther along the axis than depicted.)

Figure 1 gives an example of the spectral distribution of common lamps. The incandescent and halogen lamps' spectral distributions cover almost the entire visible spectrum (approximately 390-700 nanometers (nm)), and both emit well into the near-infrared (near-IR) wavelengths (700 nm to 1 micron). Figure 1 also includes the spectrum for a fluorescent lamp. Note that this spectrum shows distinctive intensity “peaks” in proximity to wavelengths associated with the colors blue, cyan, green, amber, and orange, while having a relatively low, flat output across the rest of the spectrum.

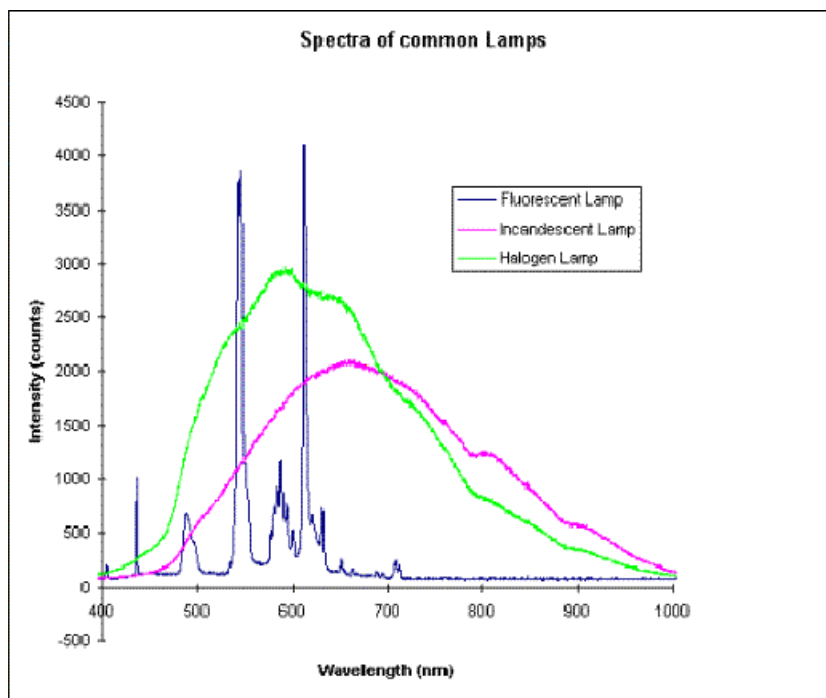


Figure 1. Spectra of common lamps².

Figure 2 shows the spectral distribution of an incandescent lamp as compared to a “cool” white LED. Note the LED peak intensity in the blue range (~450 nm), where the incandescent lamp peaks closer to red (650 nm).

²http://www1.union.edu/newmanj/Physics100/Light%20Production/producing_light.htm

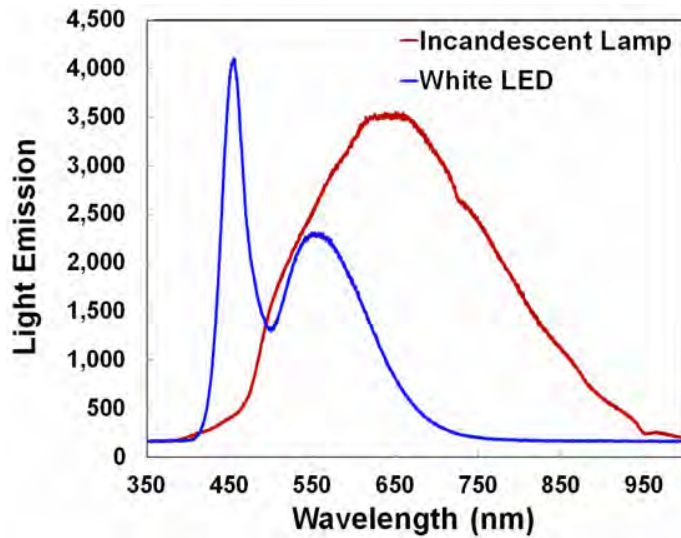


Figure 2. Spectral distribution of an incandescent lamp as compared to a specific white LED³.

Figure 3 shows the spectral distribution of the proposed two-color signal (cyan and red-orange) and the spectral distribution of a “cool” white LED. Output for the cyan is limited to an approximate 100 nm band, with the highest wavelength approaching 575 nm, while the red-orange output, though centered about a higher wavelength, is nearly non-existent above 660 nm.

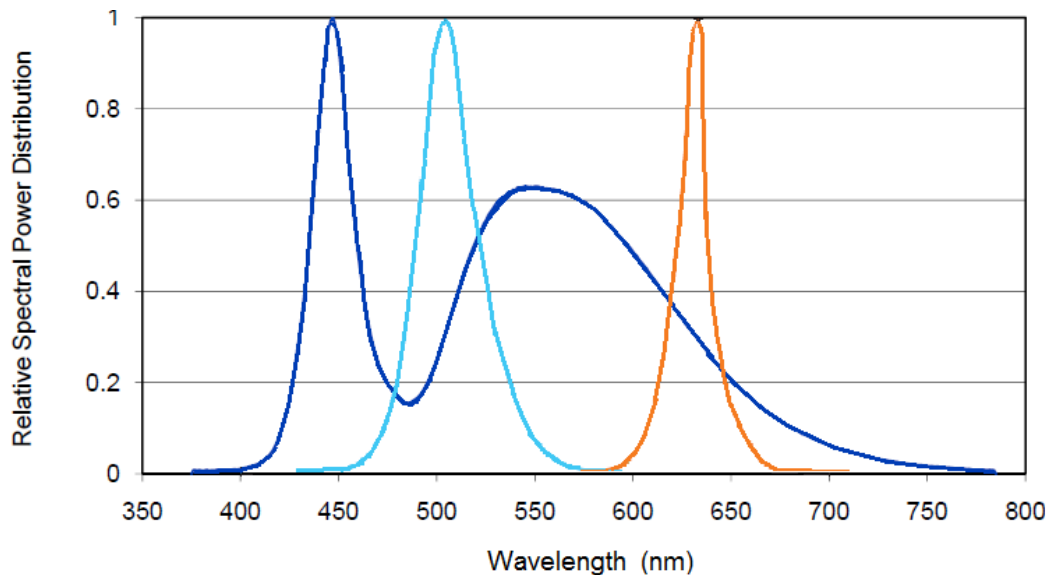


Figure 3. Spectral distribution of a “cool” white LED compared to cyan and red-orange LEDs⁴.

Note: Though the Figure 3 vertical axis label reads “Relative Spectral Power Distribution,” the figure does not depict absolute intensities for a given power input between the color LEDs and the white LED.

³ <http://www.jameco.com/Jameco/workshop/puzzler/puzzler14correct.html>

⁴ Adapted from “Luxeon® Rebel and Luxeon® Rebel ES Color Portfolio and Luxeon® General Purpose White Portfolio; <http://www.lumileds.com/uploads/265/DS68-pdf> and <https://www.sparkfun.com/datasheets/Components/LED/SMD/COM-09635-DS64.pdf>

3 PRELIMINARY NVIS EXPERIMENTS

RDC received two NVIS (with minus-blue filters) units from the Aviation Logistics Center for testing. As RDC had no recent NVIS familiarity, the project informally contacted a CG helicopter aircraft commander to get input as to how the NVIS is actually used in flight, and other observations.

The aviator and two other helicopter pilots participated in a thorough question and answer teleconference with the project team and offered different operational perspectives. All discussed high intensity light “halo” effect that could easily mask other signals. One noted that red LED obstruction lights did not appear as “visible” with NVIS as when viewing with the unaided eye; another discussed using “IR” beacons in hostile territory to clearly mark forces in need of evacuation, and all mentioned that while conducting maritime search, ambient or background lighting (clutter) did not necessarily affect the NVIS, as the aviators looked “downward” during a search rather than at the horizon where one would see the bulk of “clutter.”

The project team decided on a series of minimal-cost lab and field experiments (pilot testing). As an initial test, an observer with the NVIS viewed a light signal generator (used in the September 2014 visual signal field testing) twenty-feet distant, in a dark photometry lab. The observer could detect all 7 signal generator colors (white, blue, cyan, green, amber, red-orange, and red), at a 4Hz, 50% duty cycle flash rate. However, some key conditions come into play: (1) the lab environment, used to test marine aids to navigation lanterns, is an almost *totally* dark space, eliminating the potential for intensification of any “stray” light by the NVIS, so the only apparent background “noise” is scintillation due to the NVIS photomultiplier tube operation, and (2) in an almost totally dark space, at twenty feet, at the lowest output settings, the signal provided significantly more luminance than at *any* real-world range (i.e. 2-6 NM). This laboratory testing showed if signal output was high enough, and background conditions were totally dark, that even with the MBF, the NVIS could detect light colors beyond the filter range.

RDC then conducted an initial field test with the visual signal generator and the NVIS. These results proved significantly different from the lab. With visual signal and observers 2 miles apart, and with signal output equivalent to that of the original field testing (4 Hz, 50% duty cycle, and peak intensity of 129 candela (red-orange) and 121 candela (cyan), only white, red, and red-orange were visible, though red was faint and red-orange barely detectable. When the test increased signal intensity to a very high level (~4000 cd peak intensity), all colors were visible, however blue, cyan, and green appeared significantly less intense in the NVIS image as compared to white, red, and red-orange. Figure 4 shows the location of the initial field test, including other key light signals.

The one color that was most visible in the NVIS was a 4719K white LED. Since time and conditions allowed, the project team reduced the white signal output until the signal was not discernible from the background lighting or NVIS photomultiplier scintillation. The NVIS could still detect the relatively-broadband white LED signal at a peak intensity of 19 cd.

This preliminary testing was not very “clean.” Intense ambient light sources (sodium-vapor parking lot illumination and building floodlights) caused significant “halo” effect or blooming which often overpowered the nearby signal generator.



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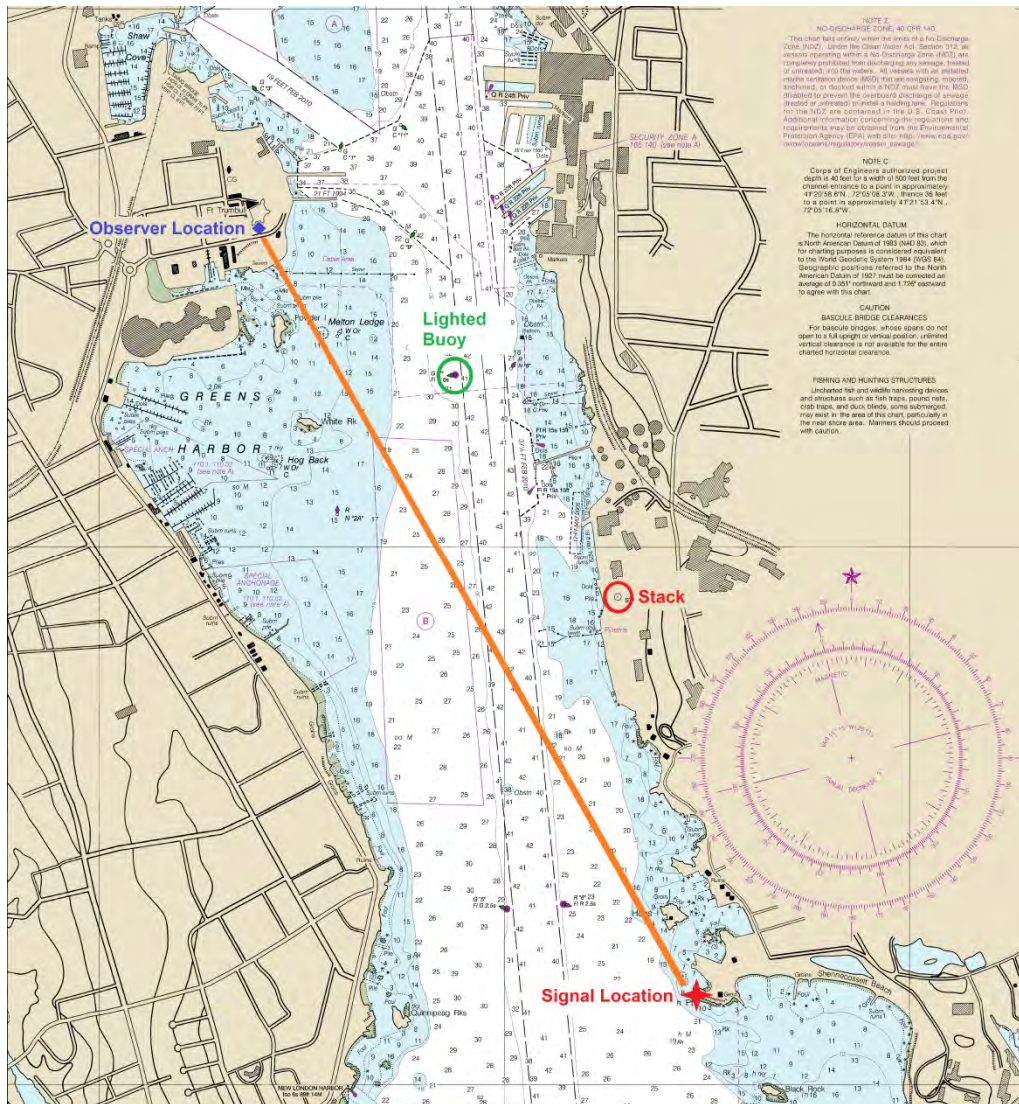


Figure 4. New London-Groton initial field test location.

As noted earlier, informal discussion with CG aviators indicated that NVIS with minus-blue filtering significantly attenuates red LED obstruction lighting signals. This was confirmed during this testing, where obstruction lighting on two stacks at 1900 yards (see Figure 4) were nowhere near as visible using the NVIS w/MBF as to the unaided eye. Of additional note, NVIS w/MBF could not image a lighted green channel buoy, at approximately 950 yards (Figure 4).

After these initial results, the RDC project team, CG Lifesaving and Fire Safety Division (G-ENE-4), the Office of Search and Rescue (CG-SAR-1), and the Office of Aviation Capabilities (CG-7112) discussed the targeted needs for effective detection through the NVIS. Consensus indicated that RDC would try to provide the NVIS wearers the same "apparent" signal as a visual searcher would see: a group flashing (4-3) 4Hz signal, visible at approximately 6 NM, throughout a hemispherical pattern, against sparse background lighting, in 10 NM visibility. For this, and to minimize power draw, the project team agreed that a near-IR signal, in the approximate *center* of the NVIS/MBF range of sensitivity (~830nm wavelength), would be the best choice to augment the visual signal.



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In order to determine the approximate near-IR signal output (mW/sr), the RDC team constructed an 830nm trial signal device and determined the approximate output-power lower-limit for detection at two miles. Using this value, we then calculated a range of power output that would suffice to have a detectable signal at 6NM, and specified construction of two, adjustable-output, near-IR signal generators.

For the two mile test (Figure 4), consensus indicated that a single LED produced a NVIS/MBF image that was discernible and could be distinguished from ambient background lighting. On-axis LED radiant power was 64 mW/sr. To produce this signal, LED electrical power use was 71 mW.



4 NEAR-IR SIGNAL TESTING

Because of the short-term nature and minimal funding for the near-IR work, the project team needed to develop a test plan paradigm that was different than the initial, vessel-based visual signal characteristic experiment from September 2014. The goal of the test was to provide NVIS wearers the same "apparent" signal as a visual searcher would see: a group flashing (4-3) 4Hz signal, visible at approximately 6 NM, throughout a hemispherical pattern, against sparse background lighting, in 10 NM visibility. Though the project retained the 6 NM range, sparse background lighting, and 10 NM visibility parameters, the signal position would remain fixed and the observers would know its location for all trials. For this we selected a signal location at Brenton Point, RI and an observer location at Scarborough Beach, Narragansett, RI (Figure 5).



Figure 5. Location for near-IR signal testing.

Testing occurred on 3 June 2015. Before testing, experimenters gave all participants an opportunity to view the nighttime scenery, especially across the open water in the direction of the signal, so the participants would have a basic idea of how the various lights at the 6 NM (and much farther) distances would appear. Experimenters tried to have all participants experience the “halo effect” that appears when high light intensity is multiplied. Since the signal location is actually in a Rhode Island State Park with an overlook, vehicle headlights occasionally passed between the observers and the signal, and in some instances, vehicles parked with their headlights pointing almost directly at the observers.

The experiment used eight participant/subjects, none of whom had anything more than the cursory experience with NVIS before the test, and two NVIS w/MBF devices. Two subjects at a time rated the signals as displayed.

At the start of the experiment, experimenters briefed the subjects that the signal operators would display the signal at a relatively high intensity for approximately 20 seconds, then the observers would “rate” the signal as to how well they could see the signal. The available rating categories were: (1) the signal is easy to see,



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(2) the signal is somewhat difficult to pick out, (3) the signal is barely distinguishable, and (4) the observer can't see it. After the observers rated the signal, the test director had the signal operators use the next, predetermined step down, until the observers viewed all seven levels of output.

Though our goal was to provide a "sparse" background lighting condition, because of vehicular traffic in the vicinity of the signal generator, including cars that parked with their headlights on, we decided that the background conditions were actually a mix of "sparse" and "substantial" background lighting. Despite this interference, most of the participants experienced either no difficulty or some difficulty picking up a near-IR signal with an output as low as 21 mW/sr. (Figure 6).

Trial #	mw/sr output	Easy to See	Somewhat Difficult to Pick Out	Barely Distinguishable	Can't See It
1	638				
2	339				
3	154				
4	75				
5	41				
6	21				
7	10				

Figure 6. Field test NVIS part 1: coarse measurement trials-rating of signal conspicuity.

Because of the higher-than desired background clutter (occasionally well above a “sparse background lighting condition”), the experiment team decided to use the 21 mW/sr signal as the “base” intensity. Recalling the discussion from the helicopter aviators, they stressed that seldom would they encounter a distress signal masked against the background lighting conditions. With this in mind, we felt confident that the 21 mW/sr signal was adequate.

As power consumption remains a primary concern, the test team then conducted a second series of tests to see if we could lower the near-IR output even further. As before, two observers at a time viewed a series of nine signals. On direction, the signal operators first displayed the 21 mW/sr signal for 20 seconds, the observers rated the signal using the same subjective language, and the director then called for a subsequent signal. Instead of using seven different intensities as in the “coarse” test, the operators displayed signal at



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21, 17, and 14 mW/sr, then repeated the order two additional times for each pair of observers. The test results are shown in Figure 7 (not sorted) and Figure 8 (sorted by output). Though the distinction among signal output levels is not as apparent as during the “coarse” measurement trials, over one-third of the responses indicated a “barely distinguishable” or “can’t see it” categorization (Figure 8) for the near-IR signal output at 17 mW/sr and 14 mW/sr.

Trial #	mw/sr output	Easy to See	Somewhat Difficult to Pick Out	Barely Distinguishable	Can't See It
1	21				
2	17				
3	14				
4	21				
5	17				
6	14				
7	21				
8	17				
9	14				

Figure 7. Field test results, near-IR/NVIS part 2: fine adjustment trials.



Trial #	mw/sr output	Easy to See	Somewhat Difficult to Pick Out	Barely Distinguish-able	Can't See It
1	21				
4	21				
7	21				
2	17				
5	17				
8	17				
3	14				
6	14				
9	14				

Figure 8. Field test results, near-IR/NVIS part 2: fine adjustment trials (sorted by signal output).



5 TWO-COLOR VISUAL DISTRESS SIGNAL DUTY CYCLE COMPARISON

In the September 2014 visual signal testing, the project team limited all but one test signal in its investigation to signals with a 50% duty cycle; i.e., for a given flash frequency, the signal “on” time was equal to the “off” time. In subsequent discussions at Radio Technical Commission for Maritime Services (RTCM) Special Committee (SC) 132 sessions for developing an actual device specification, prospective manufacturers and vendors raised the duty cycle issue as a point of contention. Though background literature for the September 2014 tests (Laxar & Benoit, 1993.) indicated that a 30%–50% duty cycle range would provide conspicuity, time and technical constraints limited our experimentation to only one test at other than a 50% duty cycle.

The project team decided to modify a visual signal generator from the September 2014 tests so as to allow a “comparison” of the 4Hz 50% duty cycle at 50 candela (cd) effective intensity against a 4Hz signal with *different* duty cycles (10%, 20%, and 30%), *while keeping the 50 cd effective intensity*. If time permitted during the near-IR/NVIS testing, the project team planned to include a duty cycle comparison.

Using the methods from the International Association of Marine Aids to Navigation and Lighthouse Authorities Recommendation E-200-4 On Marine Signal Lights: Part 4 – Determination and Calculation of Effective Intensity (IALA, 2008), the project team determined the target, peak intensities necessary to maintain an effective intensity of 50 candela at various duty cycles for a 4Hz signal. These are given in Table 1.

Table 1. Target peak intensities to provide a 50 cd signal at 4Hz.

4 Hz on time + off time	Percent Duty cycle (%)	Duration of Discernible Flash (sec)	Target Peak Intensity
0.25	50	0.125	130.0
0.25	30	0.075	183.3
0.25	20	0.050	250.0
0.25	10	0.025	450.0

As an example to maintain the 50 cd effective intensity at a 10% duty cycle, the intensity of the discernible flash would need to be 450 cd.

In reality, due to the limitations of the signal generator control circuitry, the *actual* peak intensities and resulting *actual* effective intensities the signal generator produced varied slightly from the target intensities. Table 2 lists these values and the difference between the actual and target effective intensities.

Table 2. Actual peak and effective intensities for duty cycle comparison.

Target Peak Intensity	Actual Peak Intensity		Actual Effective Intensity		Δ Actual - Effective (%)	
	Red-Orange	Cyan	Red-Orange	Cyan	Red-Orange	Cyan
130	129	121	49.62	46.54	0.8%	6.9%
183.3	183	183	49.91	49.91	0.0%	0.0%
250	241	257	48.20	51.40	3.6%	-2.8%
450	428	418	47.56	46.44	4.9%	7.1%

The project team conducted the visual signal duty-cycle comparison on 3 June 2015, immediately after the testing described in Section 4. The signal generator team and observers were in the same locations as depicted in Figure 5. For the visual signal testing, the experiment presented a random order of duty cycle signals; each signal duty cycle presented four times, for approximately 20 seconds, for a total of 16 trials. Observers used the same descriptive ranking system as for the near-IR/NVIS testing in Section 4, but for the visual duty-cycle tests, subjects observed and rated the signals simultaneously. Figure 9 shows the results of the duty cycle comparison. From the limited sample size, with observers alerted to the signal location, for almost all opportunities, except for a few instances, observers rated signals of all duty cycles as “easy to see.”



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Trial #	Duty Cycle %	Target peak cd	Actual cd Red- Org	Actual cd Cyan	Easy to See	Somewhat Difficult to Pick Out	Barely Distinguishable	Can't See It
4	50	130	129	121	█	█		
6	50	130	129	121	█	█		
11	50	130	129	121	█	█		
13	50	130	129	121	█	█		
2	30	183	183	180	█	█		
7	30	183	183	180	█	█		
9	30	183	183	180	█	█		
15	30	183	183	180	█	█		
3	20	250	241	257	█	█		
5	20	250	241	257	█	█		
12	20	250	241	257	█	█		
14	20	250	241	257	█	█		
1	10	450	428	418	█	█		
8	10	450	428	418	█	█		
10	10	450	428	418	█	█		
16	10	450	428	418	█	█		

Figure 9. Field test results, two-color signal duty cycle comparison.



6 CONCLUSIONS

To make the two-color visual distress signal detectable through the NVIS/MBF combination, adding a near-IR signal (830 nm) at a power output of 21 mW/sr will suffice.

The limited two-color duty cycle comparison testing did not indicate any significant difference between a 50% duty cycle, and duty cycles of 10%, 20%, and 30%, *provided*, the signal projected at 50 cd *effective* intensity; i.e., for a 10% duty cycle, 4Hz signal, the actual intensity of each discernible flash would be 450 cd to achieve the 50cd *effective* intensity.



7 RECOMMENDATIONS

This work modifies the recommendations from the March 2015 report, “Alternatives to Pyrotechnic Distress Signals; Laboratory and Field Studies.” The CG R&D Center Alternatives to Pyrotechnics Project recommends that the Coast Guard’s Office of Design and Engineering Standards adopt the following characteristic for an LED Visual Distress Signal Device:

- Two colors: cyan and red-orange, in an alternating-color pattern, in groups of three to four flashes per group. (In the field tests, the cyan was four flashes, and the red-orange was three flashes.)
- A flash frequency of 4Hz, with duty cycle between 10% and 50% duty cycle, with no more than 250 milliseconds between any groups of single-color flashes.
- A minimum effective intensity of ≥ 50 cd.
- A near-IR component at 830 nm, with power output of 21 mW/sr, flashing at the same rate as the two-color flash.



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