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Daytime Distress Signal Effectiveness

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16. Abstract (MAXIMUM 200 WORDS)

This report details work on behalf of the Coast Guard Office of Design and Engineering Standards, Life Saving and Fire Safety Division (CG-ENG-4) to determine the daytime efficacy of an electronic visual distress signal, particularly as a comparable alternative to pyrotechnic flares, for recreational vessels in the United States (US). The Office of Search and Rescue (CG-SAR) and the Office of Boating Safety and Auxiliary (CG-BSX) played a major role in helping frame the desired test objectives. The report presents methods and results of field tests comparing conspicuity of hand-held flares, an orange distress flag, a signal mirror, human hand-waving, and a flashing, light-emitting diode (LED) signal. The LED signal characteristic is a group alternating, cyan (Cy) and red-orange (RO) color, 4 Hertz (Hz) flashing the SOS pattern at 50 candela (cd) effective intensity, as recommended in earlier work.

The project team conducted two full-scale field tests that yielded 759 human subject ratings of distress signal conspicuity at a one-half mile range. Test results varied greatly between sunny and cloudy conditions, with observers rating almost all signals as more conspicuous in cloudy conditions.

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EXECUTIVE SUMMARY

In May 2018, the Coast Guard Research and Development Center (RDC) successfully completed work for the Office of Engineering and Design Standards, Life Saving and Fire Safety Branch (CG-ENG-4) to develop a SOS light emitting diode (LED) nighttime distress signal for recreational vessels as an alternative to a 500 candela (cd) red hand flare. In June 2018, CG-ENG requested RDC undertake a follow-on effort to determine effectiveness of existing daytime distress signals and whether the SOS LED signal developed in the previous work, provided an equivalent to those signals. The underlying goal was to determine whether the project might yield information to update recreational vessel distress signal carriage requirements, and if project results could apply to Safety of Life at Sea (SOLAS) guidelines.

RDC conducted extensive field-testing of existing daytime distress signals and the LED signal characteristic. In multiple pre-tests, researchers compared daytime conspicuity of the SOS flashing LED signal with that of existing/approved visual distress signal devices (hand-held flares and an orange distress flag) along with commonly recognized signaling methods (a signal mirror and human hand-waving) at various ranges. RDC discussed pre-test results with project stakeholders, and the sponsor agreed that RDC should conduct full-scale tests at one-half mile range.

Testing included 759 human subject observations and ratings of distress signal visibility. In all conditions, observers rated a rigid, orange distress flag and an orange smoke signal as far more easy to see than either the LED signal or the 500 cd red hand flare. While tested in only sunny conditions, observers unanimously rated both a SOLAS hand flare and a signal mirror as "easy to see.[1]" However, pre-test trials indicated the signal mirror is generally effective only in the hands of a capable user, while the SOLAS flare, at 15,000 cd, has thirty times the intensity of the 500 cd red hand flare.

Analysis indicated a statistically-significant difference in ratings between the SOS flashing LED signal and 500 cd red hand flare during combined, sunny or overcast daytime conditions, at ½ mile range. In all cases, observers could clearly see the signal boat, and knew exactly where they could expect to see the signal. Observer responses indicated that *neither* the 500 cd red hand flare nor the 50 cd flashing SOS signal were attention-getting during sunny conditions. Observers generally rated the two as "hard to see" or "can't see at all" during sunny conditions. In cloudy conditions, there was no statistically-significant difference in ratings between the SOS flashing LED signal and 500 cd red hand flare.

The results of this project show that certain daytime distress signals are only effective at relative close range, and under certain conditions. A combination of signals may provide a better visual detection paradigm. RDC recommends stakeholders use these results to increase public and responder awareness that generally accepted distress signals when used in combination, both electronic and visual, may yield more-predictable results.

[1] The experiment trials used four categories for observer ratings: "easy to see," "somewhat hard to see," very hard to see," and "can't see at all."

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

cd	candela
CFR	Code of Federal Regulations
CG	Coast Guard
CG-BSX	Coast Guard Office of Boating Safety and Auxiliary
CG-ENG-4	Coast Guard Office of Design and Engineering Standards, Life Saving and Fire Safety Branch
CGHQ	Coast Guard Headquarters
CG-SAR	Coast Guard Office of Search and Rescue
GPS	Global Positioning System
Hz	Hertz
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
LED	Light-Emitting Diode
NOAA	National Oceanic and Atmospheric Administration
RDC	Research and Development Center
SOLAS	Safety of Life at Sea
US	United States
VDSD	Visual Distress Signal Device
VHF-FM	Very High Frequency-Frequency Modulated

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1 BACKGROUND

1.1 Pyrotechnic Flares

To signal distress, mariners commonly use pyrotechnic flares as a type of visual distress signal device (VDSD). Flares do have drawbacks, including potential to injure the user, cause fire on a vessel or liferaft, and associated storage and disposal concerns. Also, the Coast Guard (CG) Office of Search and Rescue (CG-SAR) has expressed concern regarding carriage requirements for devices (flares) that may not be as effective as other distress notification means (i.e., marine electronics).

1.2 Consideration of Light-Emitting Diode (LED) Signals

In conjunction with CG-SAR, the CG Lifesaving and Fire Safety Division (CG-ENG-4) and the Office of Boating Safety and Auxiliary (CG-BSX) sought support from the CG Research and Development Center (RDC) to establish criteria to evaluate light-emitting diode (LED) devices as maritime distress signals. The RDC executed a multi-year project effort that resulted in a specification for an LED signal characteristic that could be an alternative to a pyrotechnic flare as a conspicuous, unique, visual maritime distress signal.

The project reviewed previous studies to improve maritime aids to navigation signals, where researchers dealt with the same primary issues: visibility of a light signal, conspicuity against complex backgrounds, and signal "effective intensity." Based on this review, the project team conducted a laboratory experiment to identify the characteristics that make a visual light signal more detectable and attention-getting, i.e. conspicuous. Following the lab tests, the project team designed and conducted a series of field tests to validate the results of the laboratory study.

The result of this work was a group alternating, cyan (Cy) and red-orange (RO) color, 4 Hertz (Hz) signal flashing the SOS pattern at 50 candela (cd) effective intensity, as documented in "Alternatives to Pyrotechnic Distress Signals; Laboratory and Field Studies" (Lewandowski, et al., March 2015). Since the project emphasized development of a nighttime signal, the original project scope did not evaluate efficacy of the signal for daytime use.

1.3 Daytime Effectiveness

On completion of the nighttime signal work, the project sponsors (CG-ENG-4, CG-SAR, and CG-BSX) desired to know if the new visual signal was effective for daytime use. This project is a follow-on effort that examines the daytime detectability/identification of the two-color signal and six other daytime signals, to establish the effectiveness of the two-color signal relative to the other daytime signals.

2 METHODS

2.1 Signal Selection

The Code of Federal Regulations (CFR), 33 CFR 175.110, lists requirements for boats to carry both day and night use visual distress signals (33 CFR, 2019). Visual distress signals currently accepted as meeting safety equipment carriage requirements for daytime use are an orange distress flag and various pyrotechnic signal devices. This project assessed whether the following signals were visible to observers at one-half mile during ***daytime*** conditions:

- Two-color group-alternating SOS flashing LED signal (developed in earlier RDC efforts).
- Red hand flare 500 candela [cd], 2 minute duration (46 CFR 160.021).
- Safety of Life at Sea [SOLAS] 15,000 cd red flare, 1 minute duration (46 CFR 160.121).
- Hand orange smoke flare, 1 minute duration (46 CFR 160.037).
- Orange distress flag for boats (46 CFR 160.072).

Additionally, the project assessed the visibility of other commonly used visual distress signals, a signal mirror and hand waving.

Since a signal mirror requires reflection of directed light, the RDC research team conducted preliminary assessment of signal mirror functionality during different lighting conditions to determine whether to include it in full-scale overcast tests. The team found that the mirror does not work when the sunlight is obscured due to clouds or a light overcast. The signal mirror only works when the sun casts a shadow.

RDC researchers considered the 500 cd red hand flare as the minimum signal for carriage requirements, i.e., it meets the carriage requirement for both night and day VDSDs. Researchers used this signal to base equivalence of the two-color group-alternating SOS LED signal. (CG-ENG-4, as project sponsor, recommended this approach.)

2.2 Distance between Signals and Ground Observers

Initial guidance from sponsors and stakeholders based "acceptance" of the LED signal as contingent on observer identification of the signal at greater than one nautical mile. In initial testing at two miles, observers could only regularly detect the orange distress flag and SOLAS rated flares. The researchers then shortened the range to one mile. At this distance, observers could identify and detect the LED signal and the 500 cd flare, but only under very limited circumstances, e.g., a heavy overcast. Because of this, the project team advised the sponsor and stakeholders of these preliminary findings, and recommended that testing at one-half mile might be the only viable test option. In further testing at the one-half mile range, observers *could* detect and identify both the 500 cd flare and the LED signal in more cases than not, albeit occasionally with some difficulty. After discussion with the project stakeholders, the project team and sponsor agreed that RDC should evaluate the effectiveness of the LED signal and the 500 cd red hand flare, along with other signal methods, at the one-half mile range.

2.3 Daytime Light and Background Condition Selection

Researchers assumed that sky, sun, and terrestrial background conditions affect an observer's ability to detect and identify a signal. Discussions with the project sponsor and stakeholders identified various conditions for investigation:

- Sky: Bright sun, broken sky (partly cloudy), light overcast, heavy overcast.
- Sun: Behind observers, behind signals, perpendicular to the line between signals and observers.
- Background: Open horizon, green vegetation, mixed structures and vegetation.

From preliminary tests, researchers noted that sky conditions, particularly the difference between bright sun and overcast to broken clouds played a significant role in observer ability to detect and identify signals. Though the research team initially considered evaluating the signals with four types of sky, three sun orientations, and three types of background, in the end, accounting for weather forecasts, vessel and observer schedules, and overall project constraints, the project team settled on two sky conditions: bright sun and moderate to heavy overcast.

2.4 Full-scale Field Tests

The concept behind the field-testing was to determine whether observers rated the LED signal equivalent to the 500 cd red hand flare. From the preliminary testing results, the project team included the other signals mentioned in Section 2.1 to arrive at a relative ranking among the entire set. Field test site selection needed to incorporate at least the sun/sky and background conditions described in Section 2.2, and the one-half mile distance from observers to signal noted in Section 2.3.

The project team put significant effort into determining a suitable location for the testing. While trying to incorporate the considerations from Sections 2.2 and 2.3 (sun/signal/observer aspect, background), and range, researchers noted that observer height of eye was also extremely important. If an observer was at a twelve-to-fifteen foot height above sea level, the observer would see blue water behind a small target boat, rather than the desired background. Because of this, the experiment planners needed to have observers as close to the water as possible, preferably at a beach. Researchers found suitable locations at Ft. Getty Park, Jamestown, RI (Figure 1 and Figure 2).

Figure 1. Location of observer positions at Fort Getty Park, Jamestown, RI.

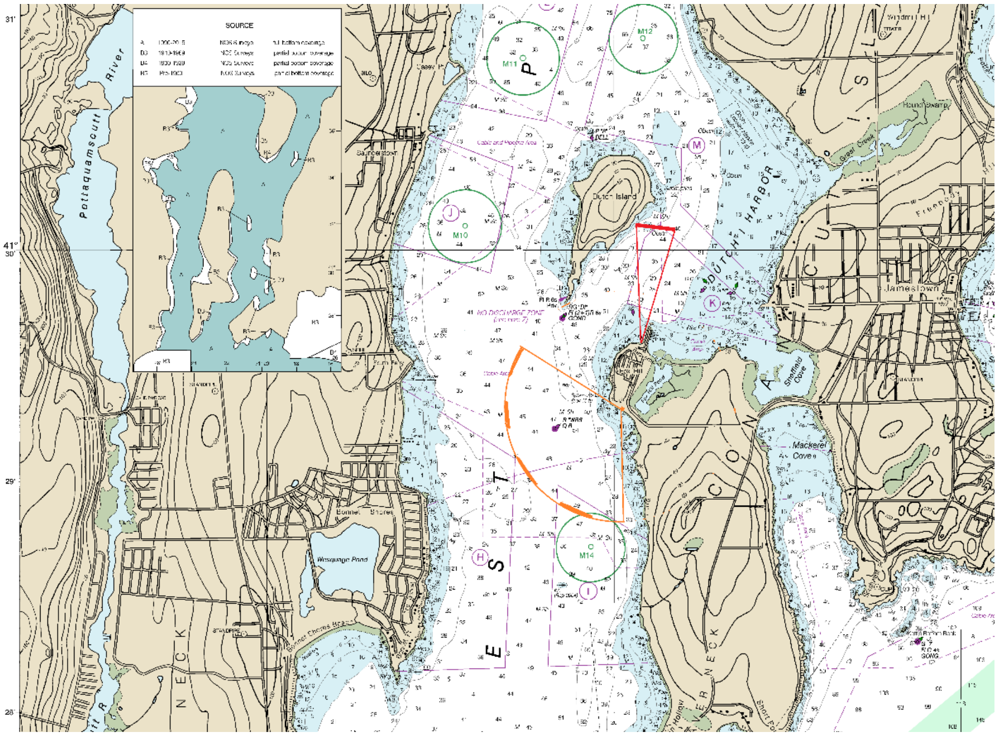


Figure 2. Arcs (orange and red) indicating boat-based, signal display locations relative to observers (NOAA chart 13223).

2.4.1 First Test (Sunny Conditions)

The first test, on 29 August 2018 from Ft. Getty Park, Jamestown, RI, required a significant amount of planning, most notably to coordinate the signal display vessel, a number of volunteer observers, and test team. For this test, the project used a CG Auxiliary vessel as the signal display vessel, and CG Auxiliarists and RDC staff as observers, all seated to have a height of eye six to ten feet above sea level. From the two locations shown in Figure 1, nine observers rated signal “visibility” as either “easy to see,” “somewhat hard to see,” “very hard to see,” or “can’t see at all.” The project conducted four test series to take best advantage of conditions with observers facing as follows:

- South-southwest: Horizon background, sun above and to observers’ left.
- Southwest: Mixed structure-foliage background, sun above and to observers’ left.
- West: Foliage background, sun above and behind observers’ left shoulders.
- North: Foliage background, sun above and behind observers.

Figure 3 shows background conditions as viewed from Fort Getty Park.

(a) Horizon background.

(b) Mixed structures and foliage background.

(c) Foliage background.

(d) Foliage background (sun behind observers).

Figure 3. Background conditions as viewed from Fort Getty Park, Jamestown, RI.

Daytime Distress Signal Effectiveness

During the testing from approximately 0930 until 1330 local time, a project engineer measured daytime luminance and illuminance values[2] using specialized meters (Figure 4).

Figure 4. Light measurement equipment.

A luminance meter (Figure 4, left) measures the amount of light emitted or reflected from a specific area of an object (in this case, the background behind and surrounding the test signal). An illuminance meter (Figure 4, right) measures the ambient light at the observers' location.

Observer participants recorded all observations on standardized data sheets (Figure 5). RDC technicians displayed VDSDs, in a pre-selected randomized order (each signal twice at each location) from a small boat approximately one-half mile offshore from the observers (Figure 6).

Observer:											
Date:			RATING				Gear				
Location	Signal #	Time	Easy to See	Some-what hard to see	Very Hard to See	Can't See At all	Cap	Sun Glasses	Binocs	Shade	COMMENTS

Figure 5. Standardized data sheet for observations.

[2] Luminance describes the amount of light emitted or reflected from a *particular area or location*; in this case, the light from the different backgrounds (horizon, mixed structure and foliage, and foliage) behind the test signal. Illuminance is the total amount of ambient light at the observer location.

Figure 6. Signal boat displaying smoke signal, green foliage background, seen from Jamestown Island.

The signal boat displayed the following VDSDs:

- Two-color group-alternating SOS flashing LED signal (50 cd).
- Red hand flare, 500 cd, 2 minute duration.
- SOLAS 15,000 cd red flare, 1 minute duration.
- Hand orange smoke flare, 1 minute duration.
- Orange distress flag for boats.
- Signal mirror.
- Hand waving.

The two observation points at Fort Getty Park faced southwestward and northwestward, respectively, to capture different sun azimuths and backgrounds (clear horizon, green foliage, and mixed development) behind the test signals. Additionally, during sunny trials, researchers recorded air clarity as a subjective measure of haze density.

2.4.2 Second Test (Cloudy Conditions)

Scheduling, logistics and weather prevented re-use of Ft. Getty Park for follow-on testing in overcast conditions. In order to complete test observations before winter, the project team chose an alternative location at Eastern Pt. Beach in Groton, CT (Figure 7).

Figure 7. Location of observer position at Eastern Pt., Groton, CT.

The project team had used this site before for preliminary testing, but vessel traffic, limited range to appropriate background conditions, and slightly elevated observer location made it less-ideal than the Ft. Getty site. The major benefit was proximity to RDC, so the project team could mobilize and recruit volunteer observers from the RDC staff on extremely short notice. In October 2018, at Eastern Point Beach, Groton, CT, nine observers participated in similar test procedures and data collection methods used during sunny conditions two months earlier, excluding the SOLAS flare and signal mirror, under moderate overcast conditions (Figure 8). Observers rated signal visibility against (a) clear horizon, (b) mixed structures and foliage, and (c) green foliage backgrounds.

(a) Horizon background (b) Mixed structures and foliage background (c) Foliage background

Figure 8. Background conditions as viewed from Eastern Point Beach, Groton, CT.

Researchers excluded the signal mirror and SOLAS flare from the second test. As the results discussion below will show, in sunny conditions, observers rated both the signal mirror and SOLAS flare as "easy to see" in all trials. Since the SOLAS flare rating is 30 times greater than the 500 cd red hand flare, the project team did not include the SOLAS flare in further testing. With the signal mirror, intermediate pre-tests showed that the signal mirror failed to produce a reflected signal during conditions when the sun casts no shadows. Thus, researchers excluded both signals from further test comparison.

For the second test, RDC technicians displayed signals from a National Oceanographic and Atmospheric Administration (NOAA) survey craft.

3 RESULTS & ANALYSIS

3.1 Preliminary Signal Visibility Assessment[3]

3.1.1 Signal Visibility during Sunny Conditions

Table 1 shows the observer visibility ratings for each distress signal according to background and sun position during testing in Jamestown, RI on 29 August 2018. The first four numerical columns in each sub-table show the number of observer responses for each visibility rating. The visibility ratings aligned to an ordinal ranking as follows:

3 - Easy to see.
2 - Somewhat hard to see.
1 - Very hard to see.
0 - Can't see at all.

[3] Appendix A is a comprehensive listing of environmental conditions and observer ratings for each test/trial for both locations

Table 1. Observer ratings for visual distress signals, sunny conditions, Jamestown, RI, 29 August 2018.

(a) Test 1 - Jamestown, RI Aug 29, 2018 Horizon background, sun above /off to observers' left					
Signal	Easy to See	Some-what hard to see	Very Hard to See	Cant See At all	Average
SOLAS Flare	18	0	0	0	3.00
Mirror	18	0	0	0	3.00
Smoke Signal	13	2	1	2	2.44
Flag	7	8	3	0	2.22
Hand Flare	3	2	6	7	1.06
LED	1	1	6	10	0.61
Hand Waving	1	2	3	12	0.56

(b) Test 2 - Jamestown, RI Aug 29, 2018 Foliage background, sun above/behind observers' left shoulder					
Signal	Easy to See	Some-what hard to see	Very Hard to See	Can't See At all	Average
Mirror	18	0	0	0	3.00
SOLAS Flare	18	0	0	0	3.00
Smoke Signal	13	5	0	0	2.72
Flag	10	6	2	0	2.44
Hand Flare	0	3	5	10	0.61
Hand Waving	0	0	4	14	0.22
LED	0	1	1	16	0.17

(c) Test 3 - Jamestown, RI Aug 29, 2018 Mixed residential background, sun above/off to observers' left					
Signal	Easy to See	Some-what hard to see	Very Hard to See	Can't See At all	Average
Mirror	18	0	0	0	3.00
SOLAS Flare	18	0	0	0	3.00
Smoke Signal	17	1	0	0	2.94
Flag	3	6	6	3	1.50
Hand Flare	0	0	5	13	0.28
LED	0	0	3	15	0.17
Hand Waving	0	0	1	17	0.06

(d) Test 4 - Jamestown, RI Aug 29, 2018 Foliage background, sun above /behind observers					
Signal	Easy to See	Some-what hard to see	Very Hard to See	Can't See At all	Average
Mirror	18	0	0	0	3.00
SOLAS Flare	18	0	0	0	3.00
Smoke Signal	13	5	0	0	2.72
Flag	12	6	0	0	2.67
Hand Flare	4	5	6	3	1.56
LED	0	2	7	9	0.61
Hand Waving	0	1	4	13	0.33

The "averages" in the right-hand column of each table indicate the number of observer responses for each rating description, multiplied by the description ordinal ranking (3, 2, 1, 0), divided by the number of observations. This gives a general indication of signal performance for each background and sun condition. As an example, for Test 3 above, to determine the average rating for the flag: [(3 x 3 (easy to see) = 9) + (6 x 2 (somewhat hard to see) = 12) + (6 x 1 (very hard to see) = 6) + (3 x 0 (can't see at all) = 0)] /18 observations, yields 1.5. Against all backgrounds and sun conditions, observers rated the signal mirror and SOLAS flare as easiest to see, and hand waving and the LED signals most difficult to see.

In Table 1, each sub-table ((a) through (d)) correlates to the test backgrounds in Figure 3: i.e., (a) Test 1, horizon background; and (b) Test 2, green foliage background, etc.

Table 2 shows the combined observer visibility ratings of the distress signals under sunny conditions.

Table 2. Combined observer visibility ratings for sunny conditions, Jamestown, RI on 29 August 2018.

Test Totals - Jamestown, RI Aug 29, 2018 All backgrounds, sun above/behind observers					
Signal	Easy to See	Some-what hard to see	Very Hard to See	Can't See At all	Average
Mirror	72	0	0	0	3.00
SOLAS Flare	72	0	0	0	3.00
Smoke Signal	56	13	1	2	2.71
Flag	32	26	11	3	2.21
Hand Flare	7	10	22	33	0.88
LED	1	3	20	48	0.40
Hand Waving	1	4	9	58	0.28

3.1.2 Signal Visibility during Cloudy Conditions

Table 3 shows the observer visibility ratings for each distress signal according to background under generally overcast conditions in Groton, CT on 23 October 2018. During Test 3, observers noted some sun poking through the broken clouds, which caused glare on the water. Against all backgrounds, observers rated the smoke signal as easiest to see, followed by the distress flag. In two of three tests, the 500 cd hand flare rated slightly more conspicuous than the LED signal. Observers rated hand waving as the most difficult to see against all tested backgrounds.

Table 3. Observer ratings for visual distress signals, cloudy conditions, Groton, CT, 23 October 2018.

(a) Test 1 - Groton, CT Oct 23, 2018 Horizon background, cloudy					
Signal	Easy to See	Some-what hard to see	Very Hard to See	Can't See At all	Average
Smoke Signal	16	0	0	0	3.00
Flag	15	1	0	0	2.94
Hand Flare	14	2	0	0	2.88
LED	13	3	0	0	2.81
Hand Waving	0	0	3	13	0.19

(a) Test 2 - Groton, CT Oct 23, 2018 Mixed background, cloudy					
Signal	Easy to See	Some-what hard to see	Very Hard to See	Can't See At all	Average
Smoke Signal	17	0	0	0	3.00
Flag	14	3	0	0	2.82
LED	8	6	3	0	2.29
Hand Flare	5	10	1	1	2.12
Hand Waving	0	0	5	12	0.29

(c) Test 3 - Groton, CT Oct 23 ,2018 Foliage background, sun coming thru clouds					
Signal	Easy to See	Some-what hard to see	Very Hard to See	Can't See At all	Average
Smoke Signal	16	2	0	0	2.89
Flag	16	1	1	0	2.83
Hand Flare	8	5	5	0	2.17
LED	5	9	4	0	2.06
Hand Waving	1	0	0	17	0.17

As in the case for the Jamestown results, each sub-table ((a) through (c)) correlates to the test backgrounds in Figure 8: i.e., (a) Test 1, horizon background; (b) Test 2, mixed structures and foliage; and (c) Test 3, foliage background. Though not apparent from the results, sunlight coming through the broken clouds periodically created glare on the water. Table 4 summarizes the total observer visibility ratings for distress signals under overcast conditions.

Table 4. Combined observer visibility ratings for cloudy conditions, Groton, CT on 23 October 2018.

Test Totals - Groton, CT Oct 23, 2018 All backgrounds, overcast conditions					
Signal	Easy to See	Some-what hard to see	Very Hard to See	Can't See At all	Average
Smoke Signal	49	2	0	0	2.96
Flag	45	5	1	0	2.86
Hand Flare	27	17	7	0	2.39
LED	26	18	6	1	2.35
Hand Waving	1	0	8	42	0.22

3.2 Lighting Condition Variability

The human eye adapts its sensitivity to accommodate vision over a wide range of light intensity. The dynamic range of the human eye is 10^{14} (about 46 f-stops on a camera). Experiment plans called for testing under a variety of lighting conditions to test the assumption that sky, sun, and terrestrial background conditions affect an observer's ability to detect and identify a signal. However, researchers needed to take advantage of conditions as available. The Fort Getty (Jamestown) tests in August were all under bright sun conditions, with initial horizon haziness that later cleared. On the other hand, the Eastern Point (Groton) tests in October had varied cloud conditions with clear horizontal visibility.

The various backgrounds under the various sun conditions produce different levels of background luminance. Researchers assumed a signal "competes" against the background luminance. Consequently, the conspicuity of a daytime distress signal is directly related to the difference between background luminance and signal intensity. Another complicating factor is the overall brightness, or illuminance, the observer encounters.

Table 5 provides observational conditions for both test series (sunny and cloudy). For the sunny conditions, the measured background luminance values are generally four to five times that of the measured background luminance in cloudy conditions. Note that during Test 2 of the Groton test, sky conditions varied from overcast to broken, with sunlight occasionally causing glare off the water, but also contributing to a much higher luminance from the green, foliage background.

Table 5. Observational conditions for sunny and cloudy conditions.

(a) Fort Getty, Jamestown, RI - August 29, 2018 (sunny)

Time	Test #	Sun Azimuth (Degrees True)	Target Azimuth (Degrees True)	Sun Altitude (Degrees)	Sky	Estimated Visibility	Illuminance (Lux)	Luminance (ft-cd/m^2)	Background
0950-1030	1	121	220	42	medium haze	8-10 NM	31,983	4,590	horizon, hazy on water
1055-1130	2	142	286	52	medium haze	8-10 NM	14,033	2,387	green foliage, shore clearly visible
1140-1210	3	159	242	56	light haze	8-10 NM	29,600	3,367	mixed foliage & structures slight haze
1300-1335	4	198	0	57	clear	8-10 NM	11,300	2,110	green foliage, clear

(b) Eastern Point, Groton, CT - October 23 2018 (cloudy)

Time	Test #	Sun Azimuth (Degrees True)	Target Azimuth (Degrees True)	Sun Altitude (Degrees)	Sky	Estimated Visibility	Illuminance (Lux)	Luminance (ft-cd/m^2)	Background
0904-	1	125	185	19	overcast	10 NM	5,030	905	horizon
0936-	2	135	11	25	dark overcast-	10 NM	9,900	160-980	green foliage
0958-	3	142	277	29	overcast	10 NM	10,100	790	mixed green foliage & structiures

Comparing the combined Jamestown averages and the combined Groton averages in Table 6, for the 500 cd hand flare and the LED signal that observers rated as "very hard to see" and "not visible at all" under sunny conditions, ratings significantly improved under cloudy conditions. (Note: the average for "hand waving"" under cloudy conditions was lower than in sunny conditions.)

Table 6. Comparison of averages under sunny and cloudy conditions.

	Jamestown (sunny)	Groton (cloudy)
Signal	Average	Average
Mirror	3.00	n/a
SOLAS Flare	3.00	n/a
Smoke Signal	2.71	2.96
Flag	2.21	2.86
Hand Flare	0.88	2.37
LED	0.40	2.37
Hand Waving	0.28	0.22

3.3 Daytime Signal Observation Analysis

3.3.1 General

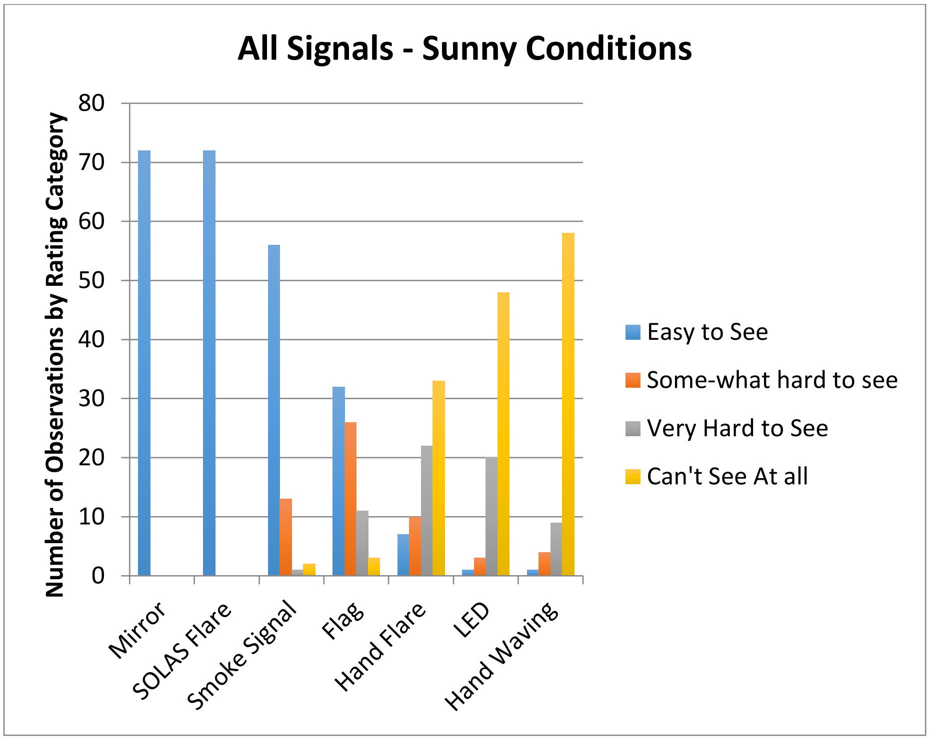
As the report discusses earlier, RDC researchers considered the relative perception of the daytime signals by a set of observers as a measure of the signals' conspicuity, hence, *how well the signals performed*. The tables in Sections 3.1 and 3.2 give summary results. These results represent 759 observation opportunities (observer ratings) over two days, bounded by the number of observer-participants per test segment, available environmental conditions, and geographic considerations for siting observers and display vessels.

Though this is a relatively large number of samples for a human vision-related test, RDC researchers conducted a series of analyses on the results in order to determine if differences in "signal performance" had statistical significance, and whether test factors (sky cover, background, etc.) may correlate to any differences.

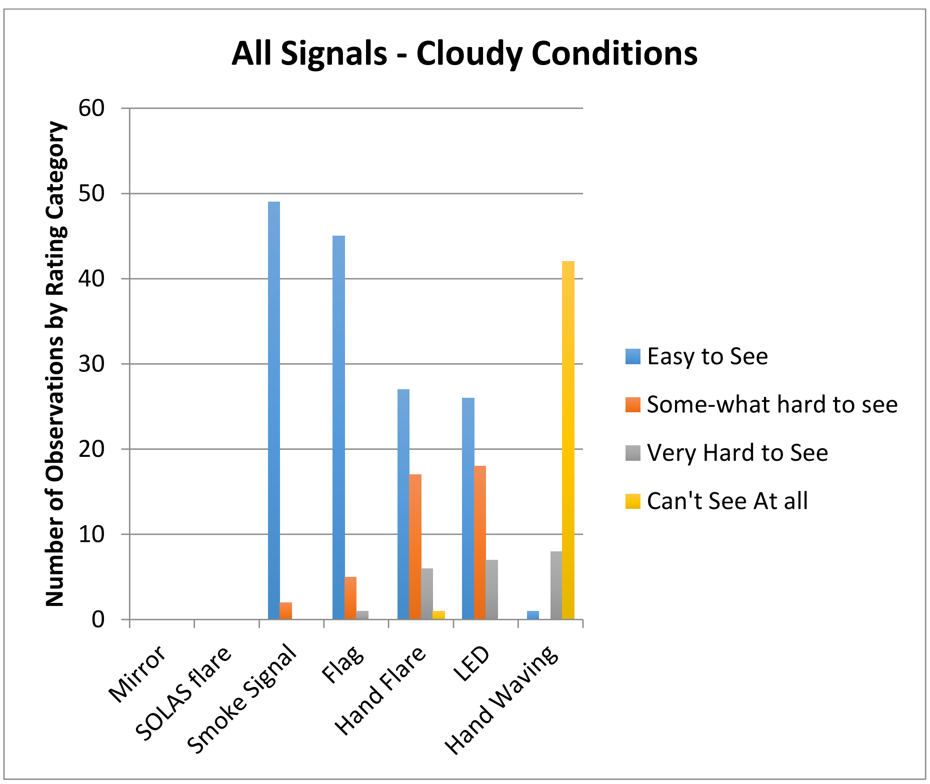
The analysis had the following variables available: (1) signal type; (2) sky condition (cloudy or sunny); (3) signal background (horizon, green foliage, or "mixed" structure and foliage); (4) horizontal angle between sun and signal as viewed from observer; (5) illuminance (total light observer experienced in a hemisphere centered on the signal); and (6) background luminance (light emitted from a ¼ degree area of the background immediately behind the signal).

3.3.2 Comparison: Sunny Versus Cloudy Conditions

The following two charts in Figure 9 indicate the number of observations by rating category for each signal in (a) sunny conditions and (b) cloudy conditions. These charts provide a simple graphic representation of the information in Table 2 and Table 4 . Because the tests had different numbers of observers, the observation counts are different for the two sky conditions. The charts clearly show the distinction between signals that are "easy to see," and those rated "can't see at all," particularly in sunny conditions. In cloudy conditions, only "hand waving" received mainly "can't see at all" ratings.



(a) Sunny conditions.



(b) Cloudy conditions.

Figure 9. Number of observations per signal by rating category.

Since responders can expect those in distress to display the signals in any daytime conditions, Figure 10 combines the results, less the SOLAS flare and signal mirror (as per the discussion in Section 2.4.2).

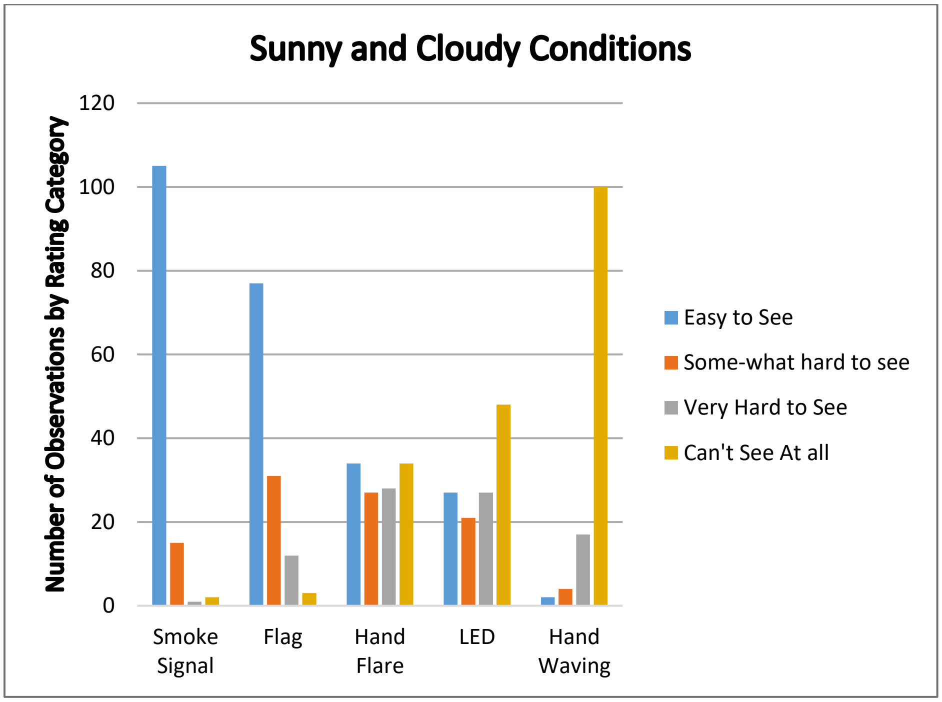


Figure 10. Number of observations per signal by rating category for remaining signals in both sunny and cloudy conditions.

Because the tests included more observations in sunny conditions than in cloudy conditions, analysts normalized the number of tests to weigh equally the observations in the two sky conditions. Otherwise, in comparisons between sunny and cloud conditions, the 72 observation results for each signal in the sunny conditions have 1.4 times the value of the 51 observation results in the cloudy conditions. Figure 11 shows the result of normalizing the two data sets on a scale of 0-100.

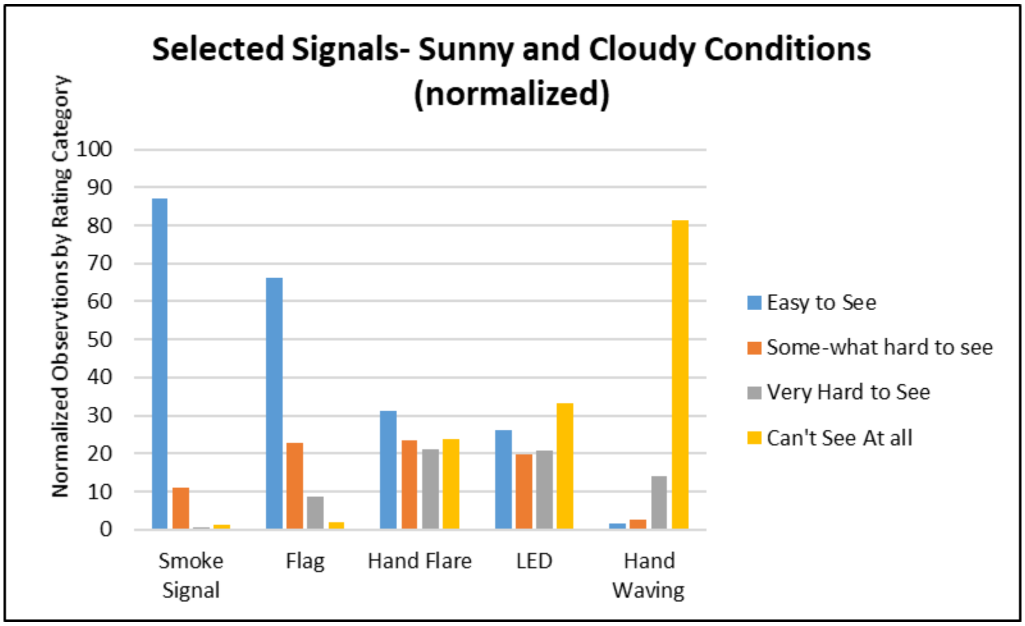


Figure 11. Normalized number of observations per signal by rating category for remaining signals in both sunny and cloudy conditions.

In either case, Figure 10 and Figure 11 clearly indicated that the smoke signal and the rigid-frame orange distress flag display far greater conspicuity than the other signals, while observers did not even see hand-waving in over 80% of the opportunities.

In terms of the "easy to see" rating, the smoke signal and the orange distress flag out-perform the other signals, regardless of sky condition.

Using the rating scale described earlier, Figure 12 shows the average combined rating for all five signals in sunny and cloudy conditions.

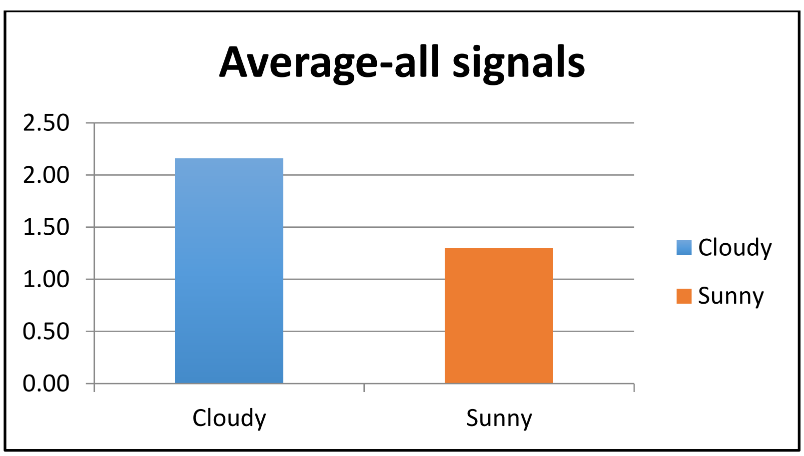


Figure 12. Average combined rating for all signals in both sky conditions.

Figure 13 shows the comparison of the average ratings by signal. Though the difference in the averages shown in Figure 12 indicate ratings almost twice as high for signals in cloudy conditions versus sunny, Figure 13 shows which specific signals have the greatest increase in performance. For cloudy conditions the red hand flare shows an approximate three-fold rating increase (0.88 vs. 2.37) while the LED signal had an almost six-fold increase (0.40 vs. 2.37).

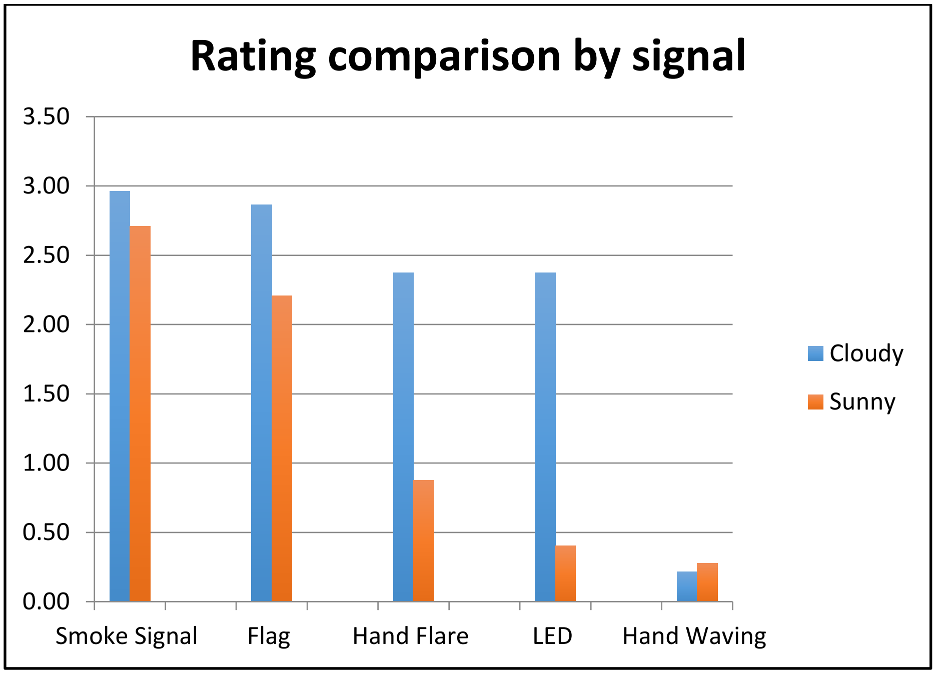


Figure 13. Average rating by signal for cloudy and sunny conditions.

3.3.3 Comparison: Background, Illuminance, Luminance, Angle between Sun Azimuth and Signal

Because of experimental constraints, the project had four tests in sunny conditions and three tests in cloudy conditions. Table 5 in section 3.2 provides the background, illuminance, and luminance details for the seven test conditions. In this comparison, the report will reference signal performance to those details. Because the two overall test series were in one of two sky conditions (with a different number of observations), the report looks at the variables in each sky condition separately, then in combination.
The one variable the project could control was background type. For the sunny condition tests, Table 7 shows the difference in azimuth angle between the signal and the sun (Δ Az), background type that included horizon (H), mixed structure and foliage (M), and green foliage (G-1, G-2), illuminance and background luminance, ratings (across all signals), and includes a cumulative rating, and the average rating across all signals.

Table 7. Conditions for each test in sunny conditions with cumulative and average ratings for all signals.

All Signals - Sunny Conditions										
Test	Δ Az	Bknd	Illum x1000 (lux)	Bknd Lum cd/m2	Easy to See	Some-what hard to see	Very Hard to See	Cant See At all	CumRatg	Average
1	99	H	31.9	4590	61	15	19	31	232	1.84
2	144	G-1	14.03	2387	59	15	12	40	219	1.74
3	83	M	29.6	3367	56	7	15	48	197	1.56
4	162	G-2	11.3	2110	65	19	17	25	250	1.98

As noted earlier, the illuminance, or overall scene brightness complicates the observer's vision, (counteracted by visors, sunglasses, or squinting), while the signal "competes" with the background luminance. Table 8 shows test conditions rank-ordering by cumulative and average ratings. (Color scheme indicates "best to worst," i.e., green, yellow, orange, and pink, for both ratings and conditions conducive to observer responses.)

Table 8. Conditions for each test, rank-ordered by observer cumulative and average ratings for all signals.

All Signals - Sunny Conditions										
Test	Δ Az	Bknd	Illum x1000 (lux)	Bknd Lum cd/m2	Easy to See	Some-what hard to see	Very Hard to See	Cant See At all	CumRatg	Average
4	162	G-2	11.3	2110	65	19	17	25	250	1.98
1	99	H	31.9	4590	61	15	19	31	232	1.84
2	144	G-1	14.03	2387	59	15	12	40	219	1.74
3	83	M	29.6	3367	56	7	15	48	197	1.56

Test 4, with both the lowest illuminance and background luminance (a green foliage background and sun almost directly behind the observers) yielded the "best" results. However, despite the greatest illuminance and background luminance present in Test 1 with a horizon background, the cumulative and average ratings across all seven signals were second highest. Surprisingly, Test 2, with green foliage, second lowest illuminance and background luminance, and sun-to-signal angle did not present high ratings.
Table 9 shows the change in both cumulative and average rating by test when removing the signal mirror and SOLAS flare from the tests. The lower test-average score resulted from removing the "high performers," as the only rating category change was in the "easy to see" rating.

Table 9. Conditions for each test in sunny conditions with cumulative and average ratings for 5 remaining signals (no mirror or SOLAS flare).

5 Signals - Sunny Conditions										
Test	Δ Az	Bknd	Illum x1000 (lux)	Bknd Lum cd/m2	Easy to See	Some-what hard to see	Very Hard to See	Cant See At all	CumRatg	Average
1	99	H	31.9	4590	25	15	19	31	124	1.38
2	144	G-1	14.03	2387	23	15	12	40	111	1.23
3	83	M	29.6	3367	20	7	15	48	89	0.99
4	162	G-2	11.3	2110	29	19	17	25	142	1.58

Table 10 shows test conditions rank-ordering by cumulative and average ratings. (Color scheme indicates "best to worst," i.e., green, yellow, orange, and pink, for both ratings and conditions conducive to observer responses.) The ranking, by rating, remains the same as the "all signals" comparison.

Table 10. Conditions for each test in sunny conditions, rank-ordered by observer cumulative and average ratings for the five remaining signals (no mirror or SOLAS flare).

5 Signals - Sunny Conditions										
Test	Δ Az	Bknd	Illum x1000 (lux)	Bknd Lum cd/m2	Easy to See	Some-what hard to see	Very Hard to See	Cant See At all	CumRatg	Average
4	162	G-2	11.3	2110	29	19	17	25	142	1.58
1	99	H	31.9	4590	25	15	19	31	124	1.38
2	144	G-1	14.03	2387	23	15	12	40	111	1.23
3	83	M	29.6	3367	20	7	15	48	89	0.99

For the cloudy condition tests, the averages are all higher, with the number of "easy to see" ratings almost double those in sunny conditions. Where all the tests in sunny conditions had nine observers, in the cloudy conditions, Test 1 and the first half of Test 2 had eight observers, while the second half of Test 2 and all Test 3 had nine observers. This shows up in Table 11, where even though the cumulative rating for Test 2 is lower than Test 3, the average rating for Test 2 is higher.

Table 11. Conditions for each test in cloudy conditions with cumulative and average ratings for five signals.

5 Signals - Cloudy Conditions										
Test	Δ Az	Bknd	Illum x1000 (lux)	Bknd Lum cd/m2	Easy to See	Some-what hard to see	Very Hard to See	Cant See At all	CumRatg	Average
1	60	H	5.03	905	58	6	3	13	189	2.36
2	20	G	9.90	980	44	19	9	13	179	2.11
3	135	M	10.10	790	46	17	10	17	182	2.02

Table 12 shows the rank-ordered tests (by average rating only), using green, orange, and pink to highlight the conditions that ostensibly would indicate “better” observational conditions. Note that Test 3, with the widest angle between the signal and the sun azimuth, and the lowest background luminance has the lowest average.

Table 12. Conditions for each test in cloudy conditions, rank-ordered by observer average ratings for five signals.

5 Signals - Cloudy Conditions										
Test	Δ Az	Bknd	Illum x1000 (lux)	Bknd Lum cd/m2	Easy to See	Some-what hard to see	Very Hard to See	Cant See At all	CumRatg	Average
1	60	H	5.03	905	58	6	3	13	189	2.36
2	20	G	9.90	980	44	19	9	13	179	2.11
3	135	M	10.10	790	46	17	10	17	182	2.02

From these comparisons, the project cannot make many conclusions as to the full effect of conditions on observer ratings. The only readily apparent commonality in both sunny and cloudy conditions is that against a mixed background of structures (houses) and foliage, observer ratings were noticeably lower than against the horizon or foliage.

3.3.4 Statistical Analysis, Comparison of Signals

This project experiment initially considered seven different daytime distress signals: 500 cd hand flare, smoke signal, hand waving, LED-SOS signal, orange distress flag, signal mirror, and a 15,000 cd SOLAS flare. As discussed in Section 2.4.2, this analysis does not include the SOLAS flare and signal mirror, though highest-rated during the tests in sunny conditions.

The experiment included 759 human observations. Without the observations associated with the SOLAS flare and signal mirror, the raw data collected consisted of 123 human observations across each of the five distress signals.

For this statistical analysis, researchers aggregated the data across all daytime environmental factors. The numerical score for each rating replaces the descriptive ratings used above. The following table (Table 13) and boxplot (Figure 14) illustrate the raw data collected.

Table 13. Aggregated responses for signals displayed at Jamestown and Groton.

Totals - Jamestown, RI & Groton, CT Both sky conditions, all backgrounds					
Signal	Easy to See 3	Some-what hard to see 2	Very Hard to See 1	Can't See At all 0	Average
Smoke Signal	105	15	1	2	2.81
Flag	77	31	12	3	2.48
Hand Flare	34	27	28	34	1.50
LED	27	21	27	48	1.22
Hand Waving	2	4	17	100	0.25

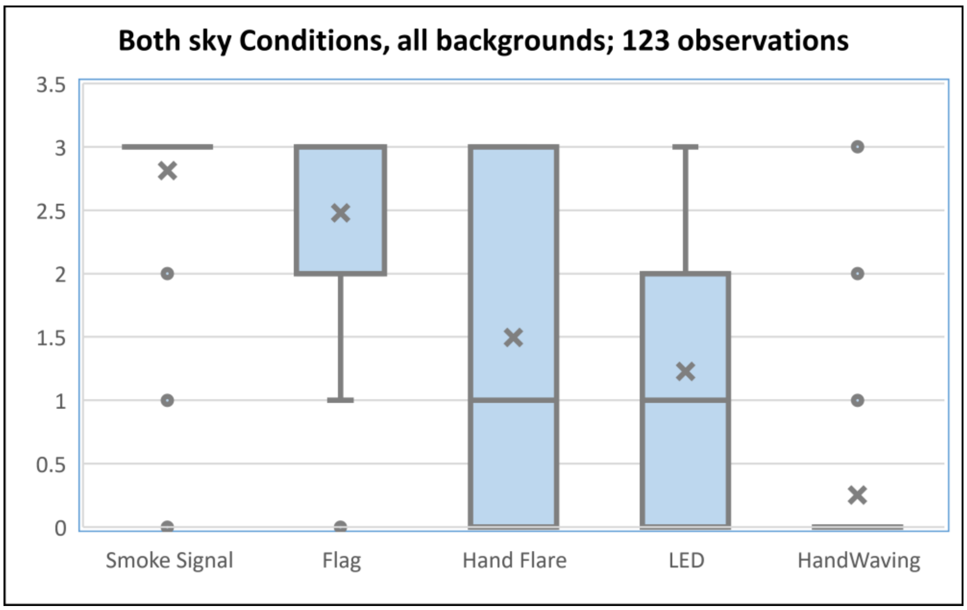


Figure 14. Boxplot for five signals, both sky conditions, all backgrounds.

The boxplot uses the 25th and 75th data percentiles to form the horizontal lines that bound each box. The horizontal line within the box indicates the median, while the 'X' represents the mean. Not all three horizontal lines are distinguishable for the Smoke Signal, Hand Waving, and Flag. Table 13 allows identification of the corresponding values. For the smoke signal, since 105 of 123 ratings were "easy to see," the 25th, 50th, and 75th percentiles align with that rating (3). On the other hand, 100 of 123 ratings for hand waving were "could not see at all," the 25th, 50th, and 75th percentiles all align with 0. For the flag, 77 of the 123 ratings were "easy to see," or 3, indicating the median for the flag aligns with the 75th percentile at the value of 3 in the boxplot. The hand flare and LED signal are different. While the median ratings are the same at 1 or "very hard to see," the 75th percentiles are at 3 and 2, respectively, while the mean ratings are between "somewhat hard to see" and "very hard to see."

To determine any statistically significant difference in the ratings for the five signals, analysts used the "Friedman Test.[4]" The Friedman Test is a non-parametric version of an analysis of variance (ANOVA) test. The assumptions of the Friedman Test are:

1. One group is measured on three or more occasions.
2. The group is a random sample from the population.
3. The dependent variable should be measured at the ordinal or continuous level.
4. Samples dos not need to be normally distributed.
5. The data consists of mutually independent samples.

The statistical analysis addressed all the assumptions. The study was limited by the number of observers available for participation in the data collection. This limitation precluded the study design from having 123 fully independent observations.

For this study, the null hypothesis of the Friedman Test was that the rating values for each distress signal were the same, and the alternative hypothesis was that at least two of the distress signals' rating values were different. The Friedman Test was run using JMP® software[5] with $\alpha = .05$ (the probability of rejecting the null hypothesis when the null hypothesis is true), and the results indicated that there is a statistically significant difference between at least two of the distress signals rating values ($p < .001$). Figure 15 shows the JMP® output for the Friedman Test.

Friedman Rank Test

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
Flag	123	487.000	369.000	3.95935	8.388
Hand Flare	123	344.000	369.000	2.79675	-1.777
HandWaving	123	185.500	369.000	1.50813	-13.043
LED	123	301.500	369.000	2.45122	-4.798
Smoke Signal	123	527.000	369.000	4.28455	11.231

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
314.7429	4	<.0001*

Figure 15. JMP® software output for Friedman Test.

Next, to determine which signal types were statistically different, analysts carried out the Wilcoxon Signed Rank Test. The analysis conducted one Wilcoxon Signed Rank Test for each pair of signals being compared. Because the red hand flare meets recreational vessel carriage requirements for both night-time and day-time distress signal mariners, the red hand flare is the basis for only four pairings. The analysis paired the hand flare with each of the other four signal types to determine if there was a statistically significant difference in ratings between each pair. The assumptions of the Wilcoxon Signed Rank Test are as follows:

1. The data consists of n values of differences of paired data.
2. The differences are measured on the ordinal or continuous level.

[4] This progression, use of the Friedman nonparametric test for repeated measures, followed by a Wilcoxon test to determine which specific mean ratings were significantly different from others is similar to the analysis in "Alternatives to Pyrotechnic Distress Signals; Laboratory and Field Studies, Report No. CG-D-04-15.".

[5] JMP® software is a statistical package that allows data visualization

3. The differences are independent.
4. The distribution of differences is symmetric about the median.

This statistical analysis addressed all assumptions. The results of each Wilcoxon Signed Rank Test indicate a statistically significant difference in the visual rating scores of the hand flare as compared to each of the other distress signals. To maintain the $\alpha = .05$ level, analysts used the Bonferroni Correction (a multiple-comparison correction used when several dependent or independent statistical tests are being performed simultaneously) resulting in a p-value of .0125 or less indicating statistical significance. The results indicate that the smoke signal ($p < .0001$) and flag ($p < .0001$) were easier to visually detect as compared to the hand flare, whereas the hand flare was easier to visually detect as compared to the hand waving ($p < .0001$) and LED ($p = .0068$).

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Smoke Signal	HandWaving	120.309	9.058897	13.2807	<.0001*	2.60000	2.40000	2.80000
Smoke Signal	LED	109.455	9.040565	12.1071	<.0001*	1.60000	1.40000	1.80000
Smoke Signal	Hand Flare	99.488	9.037839	11.0079	<.0001*	1.40000	1.20000	1.60000
LED	HandWaving	80.008	9.044915	8.8456	<.0001*	1.00000	0.80000	1.20000
Smoke Signal	Flag	34.276	9.013109	3.8030	0.0001*	0.20000	0.20000	0.40000
LED	Hand Flare	-24.431	9.034587	-2.7042	0.0068*	-0.20000	-0.40000	0.00000
Hand Flare	Flag	-84.789	9.033305	-9.3862	<.0001*	-1.00000	-1.20000	-0.80000
HandWaving	Hand Flare	-93.626	9.052706	-10.3423	<.0001*	-1.20000	-1.40000	-1.00000
LED	Flag	-98.561	9.036864	-10.9065	<.0001*	-1.40000	-1.60000	-1.00000
HandWaving	Flag	-118.585	9.058166	-13.0915	<.0001*	-2.20000	-2.40000	-2.00000

Difference Plot

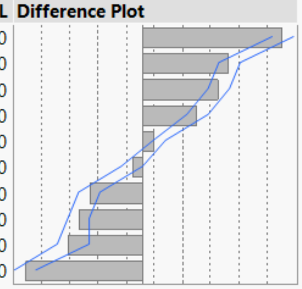


Figure 16. JMP® software output for Wilcoxon Test.

To further explore the differences in the distress signal ratings, analysts used the same statistical techniques and addressed the each day's data separately. The goal of this additional analysis is to statistically understand how the sunny versus cloudy conditions affected the signal ratings. Figure 17 and Figure 18 show boxplots for the data broken down by each day, followed by the statistical analysis.

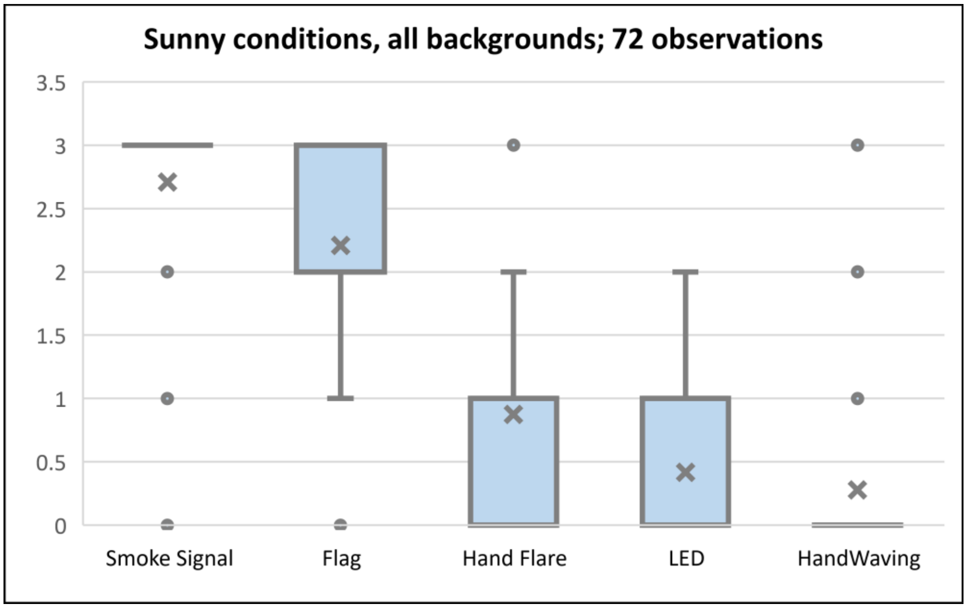


Figure 17. Boxplot for 5 signals, sunny conditions, all backgrounds.

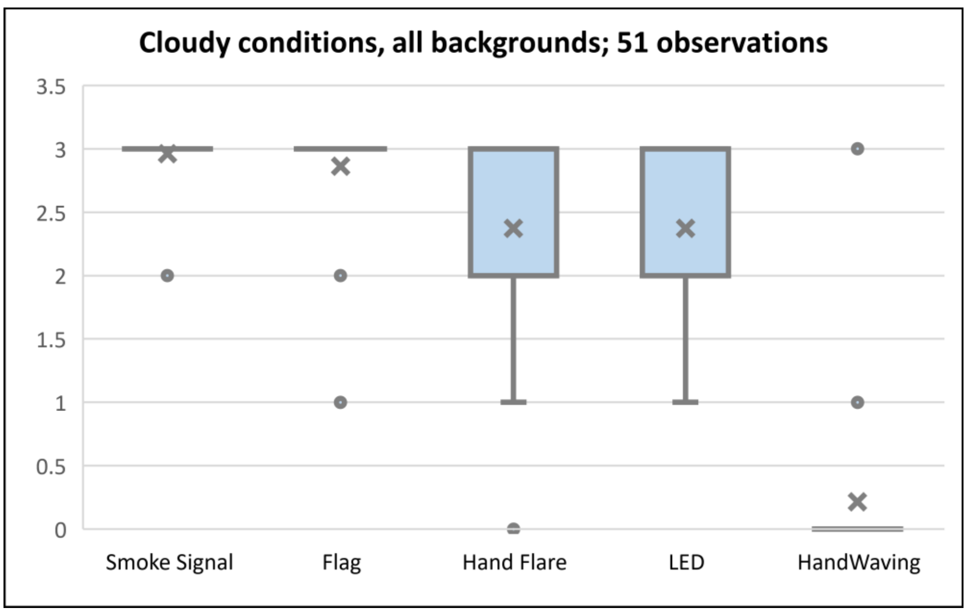


Figure 18. Boxplot for 5 signals, cloudy conditions, all backgrounds.

Day 1 (sunny/clear conditions) had 72 observations. The results of the Friedman Test (Figure 19) indicated there was a statistically significant difference between the median ratings of at least two of the distress signals ($p < .0001$). Analysts again used the Wilcoxon Signed Rank Test to compare (pairwise) the hand flare to the other four signal types. Again, analysts applied the Bonferroni Correction, resulting in a p-value less than .0125 indicating statistical significance at the $\alpha = .05$ level. These results aligned with the original analysis, indicating that the smoke signal ($p < .0001$) and flag ($p < .0001$) were easier to visually detect as compared to the hand flare, whereas the hand flare was easier to visually detect as compared to the hand waving ($p < .0001$) and LED ($p = .0004$). Figure 19 shows the JMP® software output results for the Friedman test and the Wilcoxon test.

Friedman Rank Test

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
Flag	72	291.000	216.000	4.04167	6.742
Hand Flare	72	189.000	216.000	2.62500	-2.427
HandWaving	72	130.000	216.000	1.80556	-7.731
LED	72	146.500	216.000	2.03472	-6.248
Smoke Signal	72	323.500	216.000	4.49306	9.664

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
195.3744	4	<.0001*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Smoke Signal	HandWaving	69.4583	6.933829	10.0173	<.0001*	2.60000	2.40000	2.80000
Smoke Signal	LED	69.0833	6.936518	9.9594	<.0001*	2.40000	2.20000	2.60000
Smoke Signal	Hand Flare	63.1528	6.938548	9.1017	<.0001*	2.00000	1.80000	2.20000
Smoke Signal	Flag	31.4167	6.914290	4.5437	<.0001*	0.40000	0.20000	0.60000
LED	HandWaving	13.9306	6.887683	2.0225	0.0431*	0.20000	0.00000	0.40000
LED	Hand Flare	-24.4167	6.912344	-3.5323	0.0004*	-0.40000	-0.60000	-0.20000
HandWaving	Hand Flare	-34.8750	6.910426	-5.0467	<.0001*	-0.60000	-0.80000	-0.40000
Hand Flare	Flag	-55.0972	6.937960	-7.9414	<.0001*	-1.40000	-1.80000	-1.20000
LED	Flag	-66.4722	6.937715	-9.5813	<.0001*	-2.00000	-2.20000	-1.60000
HandWaving	Flag	-67.4167	6.936175	-9.7196	<.0001*	-2.00000	-2.20000	-1.80000

Difference Plot

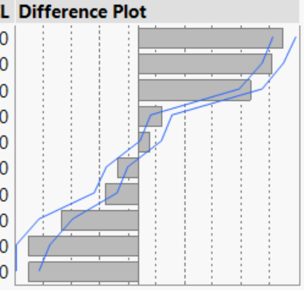


Figure 19. JMP® software output for Friedman Test and Wilcoxon Test, sunny conditions, 5 signals.

Day 2 (cloudy conditions) had 51 observations. The results of the Friedman Test (Figure 20) indicated that there was a statistically significant difference between the median ratings of at least two of the distress signals ($p < .0001$). Analysts again used the Wilcoxon Signed Rank Test to compare (pairwise) the hand flare to each of the other four signal types, and used the Bonferroni Correction to result in a p-value less than .0125 indicating statistical significance at the $\alpha = .05$ level. The results for these overcast conditions were as follows: the smoke signal ($p < .0001$) and flag ($p < .0001$) were easier to visually detect as compared to the hand flare, whereas the hand flare was easier to visually detect as compared to hand waving ($p < .0001$). Finally, the analysis indicated no statistically significant difference between the hand flare and LED signal ($p = .8822$) for the cloudy conditions. Figure 20 shows the JMP® software output results.

Friedman Rank Test

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
Flag	51	196.000	153.000	3.84314	4.982
Hand Flare	51	155.000	153.000	3.03922	0.232
HandWaving	51	55.500	153.000	1.08824	-11.297
LED	51	155.000	153.000	3.03922	0.232
Smoke Signal	51	203.500	153.000	3.99020	5.851

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
150.0108	4	<.0001*

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.95996	0.05

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Smoke Signal	HandWaving	50.9020	5.809738	8.76149	<.0001*	2.80000	2.80000	3.00000
LED	HandWaving	49.8235	5.817035	8.56511	<.0001*	2.20000	2.00000	2.40000
Smoke Signal	LED	33.2157	5.648663	5.88027	<.0001*	0.40000	0.20000	0.80000
Smoke Signal	Hand Flare	31.6471	5.673646	5.57791	<.0001*	0.60000	0.20000	0.80000
Smoke Signal	Flag	5.1569	5.589150	0.92266	0.3562	0.00000	0.00000	0.20000
LED	Hand Flare	-0.8431	5.691701	-0.14813	0.8822	0.00000	-0.20000	0.20000
Hand Flare	Flag	-27.6667	5.660525	-4.88765	<.0001*	-0.40000	-0.60000	-0.20000
LED	Flag	-29.2941	5.634210	-5.19933	<.0001*	-0.40000	-0.60000	-0.20000
HandWaving	Hand Flare	-49.4706	5.822822	-8.49598	<.0001*	-2.20000	-2.40000	-2.00000
HandWaving	Flag	-50.7843	5.806078	-8.74675	<.0001*	-2.80000	-3.00000	-2.60000

Difference Plot

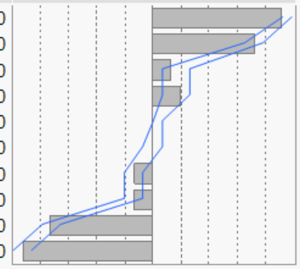


Figure 20. JMP® software output for Friedman Test and Wilcoxon Test, cloudy conditions, 5 signals.

4 CONCLUSIONS

4.1 Data Comprehensiveness

The data this project gathered includes observer ratings of VDSD conspicuity under two daytime sky conditions and against three backgrounds. The project team is unaware of any other tests involving daytime distress signals that include 633 observations[6] for comparative analysis. Though the testing did not include additional ambient lighting conditions, particularly near dusk/late afternoon, the project team is confident that the results are representative of daylight conditions.

4.2 Daytime Distress Signals, In General

In sunny conditions, the two best signals, with almost unanimous ratings of "easy to see" were the signal mirror and the SOLAS hand flare. The signal mirror requires a visible sun while the SOLAS hand flare has 30 times the luminous intensity of the 500 cd red hand flare. (Of note, a SOLAS flare costs approximately 2-1/2 times a 500 cd hand flare.) The smoke flare and the fluorescent orange signal flag received higher average ratings than the 500 cd hand flare and the SOS LED under both conditions.

Throughout previous nighttime distress signal experiments, RDC researchers frequently referenced the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) "technical recommendations." IALA has a technical recommendation for a signal in daylight, which allowed

[6] Though testing included 759 observations with the SOLAS flare and signal mirror, the project did not include the SOLAS flare and signal mirror ratings in the comparative analysis as noted in Section 2.4.2.

consideration of previous navigation signal work (IALA, 2008). IALA guidance includes recommendations for daytime signals and effective visible range. RDC staff reviewed these IALA recommendations to contextualize field results and better evaluate LED signal brightness requirements. As the results and analysis show, ambient sky conditions, and their effect on illuminance and background luminance during testing had a major impact on the conspicuity of light signals during the day.

For the conditions examined, the IALA information suggested that to provide an identifiable signal at a nominal range of one-half mile, assuming metrological visibility of 10 nautical miles, a signal's luminous intensity must be greater than 1600 cd. From the general trend in test observations between the sunny and cloudy conditions, background luminance and overall ambient lighting (illuminance) seem to play a role. However, in both the sunny and cloudy conditions, when comparing background type, observer ratings were lower when the observers viewed the signals against a "mixed" background of structure and foliage. The project did not examine lower-light conditions. Specifically, since the fluorescent orange distress flag relies on ambient light (illuminance) for its luminous intensity, the project did not consider at what diminished level of illuminance the distress flag ceases to fluoresce at a luminous intensity that provides an identifiable signal.

4.3 SOS Flashing LED Equivalency

During *combined* sunny and cloudy conditions, observer ratings indicated a statistically significant difference in the conspicuity of the SOS flashing LED and the 500 cd red hand flare. Sunny conditions exacerbate this difference, with the 500 cd hand flare mean rating approaching "very hard to see," while the SOS LED mean rating was closer to "can't see at all." In cloudy conditions, analysis indicated no significant difference between the two signals.

4.4 Potential Regulatory Impact

According to IALA (2008) technical recommendations for daytime signals and their effective visible range, interpolation suggests 1600-4000 cd luminous intensity for daytime signal effectiveness at ½ mile. Neither the 500 cd red hand flare nor the 50 cd flashing SOS LED approach this "recommended" intensity. The SOLAS flare, with its 15,000 cd intensity obviously exceeds the suggested intensity by up to an order of magnitude, and proved "easy to see" in bright sun, regardless of background or sun angle.

As noted in Section 2.2, the original input from the project sponsor and stakeholders indicated the goal to have researchers compare signals at one nautical mile. Observers could not readily identify many of the signals at one-mile distance, nor the SOS flashing LED or the approved 500 cd red hand flare at one-half mile distance under sunny conditions. The statistical analysis in Section 3.3.4 does not allow the project to conclude the red hand flare and the SOS LED signals are equivalent

5 RECOMMENDATIONS

This project followed on previous RDC project work to determine alternatives to pyrotechnic distress signals. The resulting two-color LED SOS signal was suitable as a nighttime signal, and the project sponsor and stakeholders wanted to know if the new visual signal was effective for daytime use. The project examined the daytime detectability/identification of the two-color signal along with other daytime signals, but results indicated neither the two-color signal nor the minimally required 500 cd red hand flare provide a large measure of signal conspicuity at ½-mile distance in sunny conditions.

Stakeholders and regulators should consider basing the need for effective daytime distress signals on functional requirements. If the goal is effective distress alerting, one signal may not suffice for expected illuminance conditions that vary from dawn to dusk, under cloudy skies or in clear conditions.

In the age of electronics, with relatively inexpensive personal beacons, cellphones, and digital selective calling radios (including handheld models), a policy council, with input from the National Boating Safety Advisory Council and National Association of State Boating Law Administrators could incorporate this as a topic for near-term discussions on distress signals.

RDC recommends stakeholders use these results to increase public and responder awareness that generally accepted distress signals when used in combination, both electronic and visual, could yield more-predictable results.

6 REFERENCES

Boating Safety Equipment Requirements, Subpart C--Visual Distress Signals. 33 CFR Part 175. (2019). Washington, DC: U.S. Government Printing Office.

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APPENDIX A. TEST OBSERVATIONS

Table A-1. Test observations, Jamestown, RI, 29 August 2018.

2018 Aug 29 - JAMESTOWN														
Trial	Test	Signal	n	Δ Az	Bknd	Sky	Illum x1000 (lux)	Bknd Lum cd/m2	Easy to See	Some-what hard to see	Very Hard to See	Cant See At all	Cum Rating	Average
1	1	Hand Flare	9	99	H	0	31.90	4590	3	1	2	3	13	1.44
2	1	Smoke Signal	9	99	H	0	31.90	4590	4	2	1	2	17	1.89
3	1	SOLAS Flare	9	99	H	0	31.90	4590	9	0	0	0	27	3.00
4	1	Hand Waving	9	99	H	0	31.90	4590	1	2	1	5	8	0.89
5	1	Mirror	9	99	H	0	31.90	4590	9	0	0	0	27	3.00
6	1	LED	9	99	H	0	31.90	4590	0	0	3	6	3	0.33
7	1	Flag	9	99	H	0	31.90	4590	3	4	2	0	19	2.11
8	1	Smoke Signal	9	99	H	0	31.90	4590	9	0	0	0	27	3.00
9	1	LED	9	99	H	0	31.90	4590	1	1	3	4	8	0.89
10	1	Flag	9	99	H	0	31.90	4590	4	4	1	0	21	2.33
11	1	Hand Waving	9	99	H	0	31.90	4590	0	0	2	7	2	0.22
12	1	Hand Flare	9	99	H	0	31.90	4590	0	1	4	4	6	0.67
13	1	Mirror	9	99	H	0	31.90	4590	9	0	0	0	27	3.00
14	1	SOLAS Flare	9	99	H	0	31.90	4590	9	0	0	0	27	3.00
1	2	Flag	9	144	G	0	14.03	2387	5	3	1	0	22	2.44
2	2	Hand Waving	9	144	G	0	14.03	2387	0	1	0	8	2	0.22
3	2	Mirror	9	144	G	0	14.03	2387	9	0	0	0	27	3.00
4	2	LED	9	144	G	0	14.03	2387	0	0	2	7	2	0.22
5	2	Hand Flare	9	144	G	0	14.03	2387	0	2	5	2	9	1.00
6	2	Smoke Signal	9	144	G	0	14.03	2387	6	3	0	0	24	2.67
7	2	SOLAS Flare	9	144	G	0	14.03	2387	9	0	0	0	27	3.00
8	2	Hand Flare	9	144	G	0	14.03	2387	0	1	0	8	2	0.22
9	2	Mirror	9	144	G	0	14.03	2387	9	0	0	0	27	3.00
10	2	Flag	9	144	G	0	14.03	2387	5	3	1	0	22	2.44
11	2	LED	9	144	G	0	14.03	2387	0	0	2	7	2	0.22
12	2	SOLAS Flare	9	144	G	0	14.03	2387	9	0	0	0	27	3.00
13	2	Hand Waving	9	144	G	0	14.03	2387	0	0	1	8	1	0.11
14	2	Smoke Signal	9	144	G	0	14.03	2387	7	2	0	0	25	2.78
1	3	Smoke Signal	9	83	M	0	29.60	3367	8	1	0	0	26	2.89
2	3	Hand Waving	9	83	M	0	29.60	3367	0	0	1	8	1	0.11
3	3	LED	9	83	M	0	29.60	3367	0	0	3	6	3	0.33
4	3	Flag	9	83	M	0	29.60	3367	1	4	3	1	14	1.56
5	3	Hand Flare	9	83	M	0	29.60	3367	0	0	2	7	2	0.22
6	3	Mirror	9	83	M	0	29.60	3367	9	0	0	0	27	3.00
7	3	SOLAS Flare	9	83	M	0	29.60	3367	9	0	0	0	27	3.00
8	3	LED	9	83	M	0	29.60	3367	0	0	0	9	0	0.00
9	3	SOLAS Flare	9	83	M	0	29.60	3367	9	0	0	0	27	3.00
10	3	Flag	9	83	M	0	29.60	3367	2	2	3	2	13	1.44
11	3	Mirror	9	83	M	0	29.60	3367	9	0	0	0	27	3.00
12	3	Hand Waving	9	83	M	0	29.60	3367	0	0	0	9	0	0.00
13	3	Hand Flare	9	83	M	0	29.60	3367	0	0	3	6	3	0.33
14	3	Smoke Signal	9	83	M	0	29.60	3367	9	0	0	0	27	3.00
1	4	Hand Flare	9	162	G	0	11.30	2110	3	3	3	0	18	2.00
2	4	LED	9	162	G	0	11.30	2110	0	1	4	4	6	0.67
3	4	Smoke Signal	9	162	G	0	11.30	2110	6	3	0	0	24	2.67
4	4	Hand Waving	9	162	G	0	11.30	2110	0	1	2	6	4	0.44
5	4	Mirror	9	162	G	0	11.30	2110	9	0	0	0	27	3.00
6	4	SOLAS Flare	9	162	G	0	11.30	2110	9	0	0	0	27	3.00
7	4	Flag	9	162	G	0	11.30	2110	7	2	0	0	25	2.78
8	4	Smoke Signal	9	162	G	0	11.30	2110	7	2	0	0	25	2.78
9	4	Flag	9	162	G	0	11.30	2110	5	4	0	0	23	2.56
10	4	LED	9	162	G	0	11.30	2110	0	1	3	5	5	0.56
11	4	Mirror	9	162	G	0	11.30	2110	9	0	0	0	27	3.00
12	4	Hand Waving	9	162	G	0	11.30	2110	0	0	2	7	2	0.22
13	4	SOLAS Flare	9	162	G	0	11.30	2110	9	0	0	0	27	3.00
14	4	Hand Flare	9	162	G	0	11.30	2110	1	2	3	3	10	1.11

Table A-2. Test observations, Groton, CT 23 October 2019.

2018 Oct 23 - GROTON													
Trial	Test	Signal	n	Δ Az	Bknd	Sky	Illum x1000 (lux)	Bknd Lum cd/m2	Easy to See	Some-what hard to see	Very Hard to See	Cant See At all	Cum Rating	Average
1	1	Hand Flare	8	60	H	1	5.03	905	6	2	0	0	22	2.75
2	1	Smoke Signal	8	60	H	1	5.03	905	8	0	0	0	24	3.00
3	1	Hand Waving	8	60	H	1	5.03	905	0	0	1	7	1	0.13
4	1	LED	8	60	H	1	5.03	905	6	2	0	0	22	2.75
5	1	Flag	8	60	H	1	5.03	905	7	1	0	0	23	2.88
6	1	Smoke Signal	8	60	H	1	5.03	905	8	0	0	0	24	3.00
7	1	LED	8	60	H	1	5.03	905	7	1	0	0	23	2.88
8	1	Flag	8	60	H	1	5.03	905	8	0	0	0	24	3.00
9	1	Hand Waving	8	60	H	1	5.03	905	0	0	2	6	2	0.25
10	1	Hand Flare	8	60	H	1	5.03	905	8	0	0	0	24	3.00
1	2	Flag	8	20	G	1	9.90	980	7	1	0	0	23	2.88
2	2	Hand waving	8	20	G	1	9.90	980	0	0	2	6	2	0.25
3	2	LED	8	20	G	1	9.90	980	3	3	2	0	17	2.13
4	2	Hand Flare	8	20	G	1	9.90	980	2	6	0	0	18	2.25
5	2	Smoke Signal	8	20	G	1	9.90	980	8	0	0	0	24	3.00
6	2	Hand Flare	9	20	G	1	9.90	980	3	4	1	1	18	2.00
7	2	Flag	9	20	G	1	9.90	980	7	2	0	0	25	2.78
8	2	LED	9	20	G	1	9.90	980	5	3	1	0	22	2.44
9	2	Hand waving	9	20	G	1	9.90	980	0	0	3	6	3	0.33
10	2	Smoke Signal	9	20	G	1	9.90	980	9	0	0	0	27	3.00
1	3	Smoke	9	135	M	1	10.10	790	7	2	0	0	25	2.78
2	3	Hand waving	9	135	M	1	10.10	790	0	0	0	9	0	0.00
3	3	LED	9	135	M	1	10.10	790	3	5	1	0	20	2.22
4	3	Flag	9	135	M	1	10.10	790	9	0	0	0	27	3.00
5	3	Hand Flare	9	135	M	1	10.10	790	3	3	3	0	18	2.00
6	3	LED	9	135	M	1	10.10	790	2	4	3	0	17	1.89
7	3	Flag	9	135	M	1	10.10	790	7	1	1	0	24	2.67
8	3	Hand waving	9	135	M	1	10.10	790	1	0	0	8	3	0.33
9	3	Hand Flare	9	135	M	1	10.10	790	5	2	2	0	21	2.33
10	3	Smoke Signal	9	135	M	1	10.10	790	9	0	0	0	27	3.00