OPTICAL DISTRESS BEACON FOR SPACE USE

Andrew Danowitz[(1)], Nathaniel Pinckney[(1)], Michael Braly[(1)], Howard Chen[(1)], Andrew Giles[(1)], Sarah L. Harris, Ph.D.[(1)], Samuel S. Osofsky, Ph.D.[(2)]

[(1)]*Harvey Mudd College, 301 Platt Blvd, Claremont, CA 91711, USA, sharris@hmc.edu*
[(2)]*The Aerospace Corporation, 2350 E. El Segundo Blvd, M1/111 El Segundo, CA 90245*
samuel.s.osofsky@aero.org

ABSTRACT

This paper describes the design of a personal, optical distress beacon for use by astronauts during space-walks. The distress beacon is located on the astronaut and is optically observable in the visible and IR spectra.

Two prototypes are presented. The first integrates with an existing picosatellite architecture. The second prototype is a distributed system, composed of a single control unit and multiple optical emitters. The emitters are placed around an astronaut's space suite and are activated wirelessly. Both prototypes use high-power LEDs, powered by buck current regulators and controlled with a PIC microcontroller. The distributed prototype is capable of emitting a 5 Hz strobe for 31 hours or flashing S-O-S for 12 hours. Each emitter has two green and two red LEDs, and is visible at distances of 0.07 miles in daylight and 0.5 miles at night. The control unit and emitters are each powered by three CR2 lithium batteries. Heat dissipation analyses and visibility testing results are included.

1 INTRODUCTION

The frequency of manned activities outside of a spacecraft is increasing. In 2007, International Space Station (ISS) crew members completed 23 extra-vehicular activities (EVAs), up 64% from 2006, and 229% from 2005. With the advent of space tourism, the frequency of EVAs could increase even more dramatically. During these EVAs, emergencies such as broken tethers or heart attacks could occur. Although astronauts have radio systems, in the event of an equipment failure or incapacitation of the space walker, an automatically-activated visual means of communicating the emergency is vital.

The proposed distress beacon system optically indicates an emergency to astronauts located within the spacecraft. The distress beacon is capable of surviving and operating in vacuum environments and flashes visual and infrared LEDs during an emergency situation, possibly indicating the type of emergency. The optical signals also aid in locating the astronaut in distress.

Distress beacons exist for terrestrial applications, but they are generally not suited for use in space because they rely on RF distress signals and are not designed to operate in vacuum environments. These terrestrial beacons use international emergency bands, 121.5 MHz and 406 MHz and specialized triangulation equipment to determine location [1]. For terrestrial emergencies, where trees, buildings, and other objects can obstruct visibility, this is preferable. In an EVA situation the distressed astronaut is typically located within sight of the manned space vehicles. Thus, visual indication of the emergency and location might be simpler and more reliable. Optical beacons also give real-time feedback as aid is directed to the distressed astronaut.

Currently astronaut emergency situations are detected by mission control, which monitors astronaut vital signs and voice communications [2]. While this system provides a continuous indication of the astronaut's health during normal operation, in the event that the radio signal is interrupted, either due to equipment failure or interference from solar flares, mission control has no accurate way to determine the condition of the astronaut. In such situations, the optical distress beacon would give a redundant, radio-independent means of communicating an astronaut's status.

In this paper, we present two prototypes for visual distress beacons designed to be used by astronauts during an emergency outside of the spacecraft. The first prototype, the Picosat Beacon, uses eighteen LED emitters and is designed to be incorporated with The Aerospace Corporation's current picosatellite architecture. The second prototype, the Distributed Wireless

Beacon, is a scalable distress beacon system. It has a single controller unit and any number of visible emitter units. Each emitter unit has four LEDs. Using three 3-volt CR2 lithium batteries, the Distributed Wireless Beacon module is able to power two LEDs at a time for up to 31 hours.

2 OPTICS TESTING AND CHARACTERIZATION

We tested a number of optical light sources for relative visibility and determined that green LEDs with a strobe frequency of 5 Hz and 20% duty cycle provided maximum visibility. The selection of green LEDs is validated by numerous physiological studies as in [3] that indicate that human eye cells are most responsive to green light.

We describe our testing and selection methods briefly in the following sections. LEDs were selected over other light sources because of their high efficiency and durability.

2.1 PRELIMINARY TESTING AND SELECTION

We tested two types and five colors of high-power LEDs, and six strobe frequencies (1 – 5 Hz and 10 Hz) to find the most visible color and strobe frequency. To help minimize power, we also tested visibility of the LEDs when driven below their maximum power using pulse-width modulation.

A quantitative comparison of power and lumens from specifications helped narrow our light source selection to Luxeon Rebel series LEDs. Luxeon Rebels were 20% more power efficient and as bright as tested Lumex LEDs.

A preliminary user test of blue, royal blue, green, and cyan LEDs was conducted with three volunteers. Each test compared a pair of colors, and participants indicated which light source was more visible or if there was no difference

During preliminary testing, no users indicated that blue or royal blue LEDs were brighter than any other color LED. Based on this result, the blue LEDs were removed from consideration.

2.2 Visibility Testing

We conducted more extensive user testing of color, strobe frequency, and duty cycle. Ten tests were conducted with six users. The users were given pair-wise comparisons of color, frequency, and duty cycle. The user could indicate no preference between the two choices. Fig. 1 shows the preferences of six users to red, cyan, and green LEDs. The color of the LED preference is indicated by the color of the graph; a test subject reporting no difference in visibility is indicated by a white bar. The green LED was preferred over other LEDs.

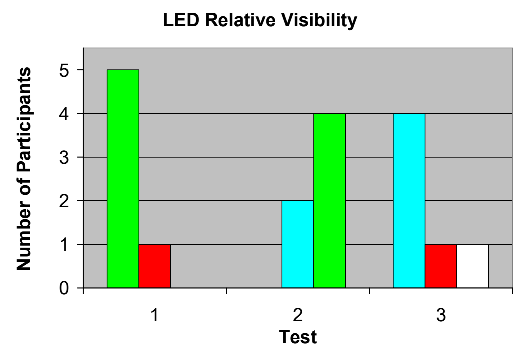

Figure 1. Color visibility test results

Table I shows the preferences of strobe frequency and duty cycle. Test subjects consistently favored a 5 Hz strobe frequency and 20% duty cycle over all other options. Based on these tests a green LED with a 5 Hz strobe and a duty cycle of 20% would be the most visible light option. In our prototypes, we chose to use red LEDs with green LEDs, alternating colors to improve visibility.

Table I. Strobe visibility test results

Test	A	B	#A	#B	No Diff
4	3 Hz	10 Hz	0	4	2
5	3 Hz	5 Hz	1	3	2
6	10 Hz	5 Hz	0	5	1
7	1 Hz	3 Hz	1	5	1
8	2 Hz	5 Hz	1	3	2
9	5 Hz, 20%	5 Hz, 50%	3	0	3
10	5 Hz, 20%	5 Hz, 80%	6	0	0

3 DISTRESS BEACON DESIGN

We designed, built, and tested two prototype distress beacons: the Picosat Beacon, an add-on beacon design that is designed for integration with The Aerospace Corporation's picosatellite architecture; and the Distributed Wireless Beacon, a standalone beacon design that uses wireless signals to control the emitters distributed across the astronaut's suit. Both designs share a common architecture and use the same circuit components and light sources.

Both designs use 3-watt Luxeon LEDs to visually indicate an emergency. The LEDs are powered by LM3405 buck current regulators, each capable of driving two LEDs.

As shown in Fig. 2, a buck current regulator operates by toggling a switch at high frequencies. Current is regulated by adjusting the duty cycle of the switch until the output current equals the desired current. The low resistance nature of this design allows buck current regulators, including the LM3405, to operate at 80-90% efficiency [3].

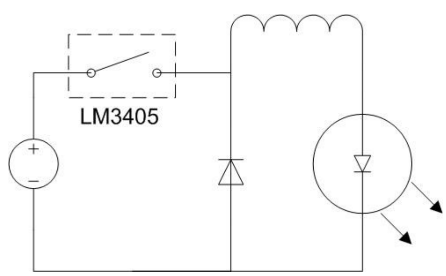

Figure 2. Simplified schematic of buck current regulator

3.1 Picosat Beacon

The Picosat Beacon is designed as an add-on board to the Aerospace Corporation's picosatellite architecture. The picosatellite architecture has a 10 cm x 10 cm x 10 cm cube form factor and has been successfully used for a number of NASA-sponsored missions, including photographing the exterior of the space shuttle [4]. The add-on beacon design is fully integrated with the picosatellite architecture: it communicates with the flight computer and other peripheral devices, and is powered by the picosatellite's batteries. Fig. 3 shows a block diagram of the Picosat Beacon design and Fig. 4 shows a mockup of the final Picosat Beacon design.

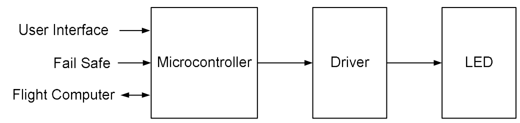

Figure 3: Picosat Beacon block diagram

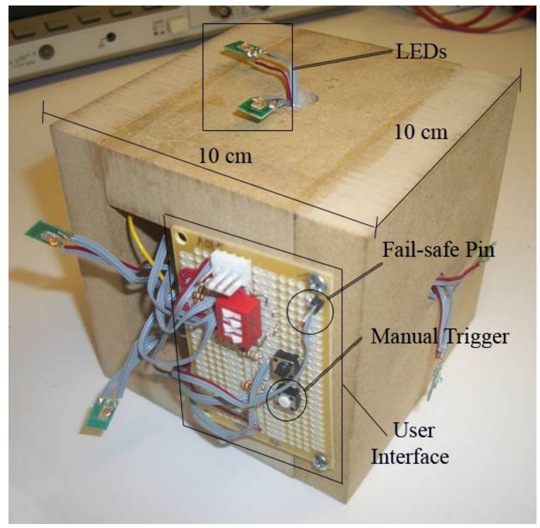

Figure 4: Picosat Beacon mockup

The Picosat Beacon has a controller board, with a PIC 18F4520 microcontroller and nine LM3405 current drivers, located within the picosat, which drives eighteen high-power LEDs (one green, one red and one infrared, per face). The mockup Picosat Beacon can be triggered either by actuating the manual trigger push-button on the user interface or by supplying a voltage to the fail-safe pin. The fail-safe pin would be triggered by a sensor such as a heart monitoring system. The prototype also supports two display modes: a high visibility 5 Hz strobe mode, which flashes all LEDs of a single color, and an S-O-S mode that uses the LEDs to signal "S-O-S" in Morse code. These modes can be selected by toggling the red DIP switches on the user interface. The LEDs are located in areas of unused surface, and they do not interfere with the current locations of cameras or antennas.

3.2 Distributed Wireless Beacon Design

Due to the physical limitations of the Picosat Beacon design, we developed a stand-alone, modularized distress beacon system. A block diagram of this system is shown in Fig. 5. The system consists of a single "master" controller unit that is placed on the front of the space suit and any number of emitter units distributed across the space suit, as shown in Fig. 6.

The astronaut activates the beacon system via a large push-button on the controller unit and, optionally, uses a series of three toggle switches to select a display mode. The device can also be activated automatically by a wireless fail-safe signal. The controller unit, upon activation, wirelessly transmits the display mode to the emitter blocks, triggering them to flash in the desired pattern. Instead of receiving display instructions continuously after activation, each emitter actives its transceiver and polls the control unit once per second to conserve power.

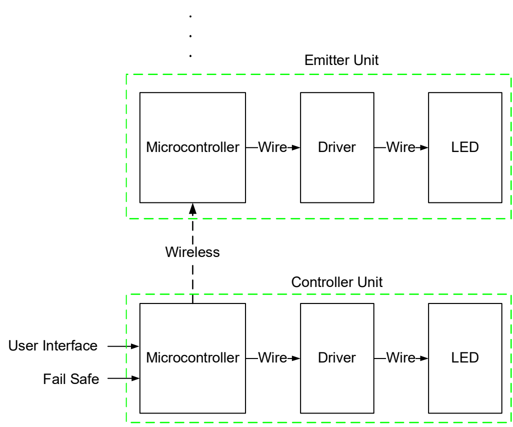

Figure 5: Distributed Wireless Beacon block diagrams

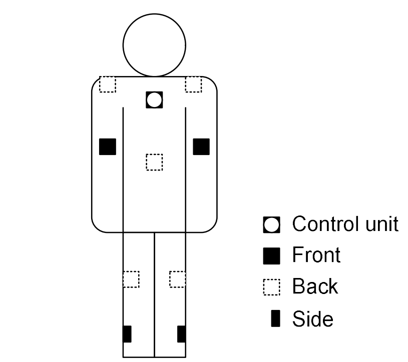

Figure 6. Locations of control unit and emitters on astronaut

Both the controller and emitter units are implemented on the single, four-layer printed circuit board (PCB), as shown in Fig. 7. The PCB contains a microcontroller, three LM3405 drivers, three CR2 lithium batteries, and a connector for an RF transceiver. Each board is capable of powering six LEDs. Due to power and heat dissipation considerations, we decided to power only two LEDs simultaneously per PCB. The current prototype alternates between two green and two red LEDs, with the last driver available to power an IR LED in future prototypes. The emitter board measures 5.5 cm x 5.9 cm. For this prototype, CR2 battery holders were unavailable, thus we neglected the size of the battery holders shown in Fig. 7. Due to its small profile, the Distributed Wireless Beacon is less obstructive to the movement of the astronaut than the Picosat Beacon.

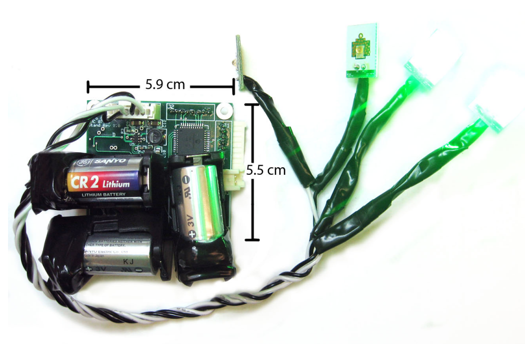

Figure 7: Photo of wireless emitter module

The RF transceiver used for the Distributed Beacon Design is the Nordic nRF24L012.4. This board was selected for its SPI interface, power saving operation modes, and ready availability of development boards and documentation.

The casing for both the emitter and controller units consists of a faceplate and backing piece. The backing piece is made of plastic to allow for better wireless signal propagation and is the same for both the emitter and receiver units. The faceplate is made of aluminum for heat dissipation purposes. A plastic prototype of the emitter faceplate design is shown in Fig. 8. It consists of a 1.3 cm thick rectangular shell with four holes for LEDs. Since only the controller unit features a user interface, the controller faceplate is a different design than the emitter faceplate.

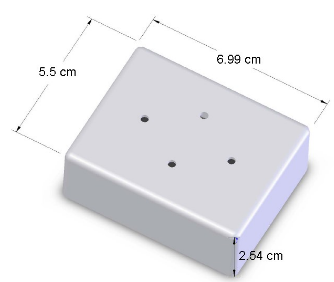

Figure 8. Prototype of emitter faceplate design

3.3 Beacon Programming

To maximize the operational lifetime of each distress beacon system, we developed several software solutions to reduce the distress beacon active and idle power. The microcontroller's "sleep" mode reduces power when the beacon is not activated; while still allowing the beacon to be triggered by the microcontroller's external interrupt pins.

We programmed the Distributed Wireless Beacon design for low wireless transceiver power consumption. During idle operation, all receivers are fully powered and waiting for an incoming fail-safe or activation signal. Once a signal has been received, the receivers on the emitter units are powered down, saving 30 mW of power. The transmitter on each emitter unit is always off during idle operation. The transmitter on the controller unit is only powered when the controller unit is triggered, sending an activation signal to the emitters.

Because of power supply constraints, both beacon prototypes timeshare activation of the LEDs, shown in **Error! Reference source not found.**. The microcontroller generates three orthogonal pulse-width modulated (PWM) signals with duty cycles of 33% (**Error! Reference source not found.**a). The LEDs do not visibly flicker when modulated above 100 Hz. This technique reduces the peak power required by the distress beacon by two-thirds. Also, by multiplying these high speed PWM signals with a lower frequency message signal (**Error! Reference source not found.**b), we can generate Morse code messages and strobe patterns for optical transmission (**Error! Reference source not found.**c).

4 BEACON TESTING AND PERFORMANCE

Both beacon designs were assembled and tested. We measured and tested visibility, power consumption, and wireless performance. A basic heat analysis shows the beacons will be able to radiate excess heat in a zero-atmosphere environment.

4.1 Beacon Visibility

We performed visibility testing of a single Distributed Wireless Beacon emitter during the day and night, to estimate the distance it is visible in space. Noon on earth approximates the distress beacon in space with daytime earth in the background. Night on earth approximates the distress beacon with stars in the background.

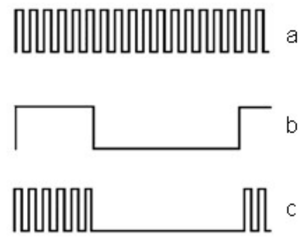

Figure 1. Example of PWM timesharing

The daytime test was conducted at noon, with the sun overhead. The emitter was placed in front of a white and a blue poster board, to approximate colors of the earth from space. The emitter was set to alternate a strobe between the green and red LEDs, and the maximum visible distance was measured. In daylight the maximum visible distance was 0.07 miles and 0.10 miles, when against the white and the blue poster board, respectively. At night we were able to see the emitter from 0.5 miles, which was the maximum visible distance of our test site. The emitter may be visible beyond 0.5 miles at night, but we were unable to test this.

4.2 Power Consumption

Experimentally-obtained power consumption for each beacon mode is listed in Table II. The full-on mode for the Picosat Beacon and Distributed Wireless Beacon includes the 33% duty cycle timesharing, as discussed earlier.

Table II: Beacon power consumption

Mode	Picosat Beacon	Distributed Wireless Beacon
Idle	0.03 W	0.03 W
Strobe	1.44 W	0.24 W
S.O.S.	3.8 W	0.63 W
Full-on	7.4 W	1.2 W

Since the wireless reciever must be powered in idle mode, the Distributed Wireless Beacon idle power is more than the Picosat Beacon design. LEDs dominate power consumption when the beacons are activated. The Picosat Beacon and Distributed Wireless Beacon power supplies have capacities of 5 W-hr and 7.5 W-hr, respectively. Run time is summarized in Table III.

Table III. Beacon run time

Mode	Picosat Beacon	Distributed Wireless Beacon
Idle	170 hr	260 hr
Strobe	3.5 hr	31 hr
S.O.S.	1.3 hr	12 hr
Full-on	0.7 hr	6 hr

4.3 Heat Dissipation

We conducted a thermal analysis to ensure that the beacon designs could dissipate heat generated by the LEDs. The LEDs are supplied 18 W and 4 W for the Picosat Beacon and Distributed Wireless Beacon, respectively. This analysis neglects LED efficiency, and thus assumes all power goes to heat. It also considers the worst-case when all LEDs activate simultaneously. Each LED is rated at 3 W, but the LEDs are pulse-width modulated with a duty cycle of 33%, and thus receive 1 W each. The Picosat Beacon has 18 LEDs and the Distributed Wireless Beacon has 4. Therefore the maximum power to dissipate is 18 W for the Picosat Beacon and 4 W for the Distributed Wireless Beacon.

According the theory of heat-transfer through black-body radiation, the amount of heat that can be dissipated by a given material is determined by

$$q = \sigma\varepsilon(T_h^4 - T_c^4)$$

where q is power dissipated per square meter, σ is the Stefan-Boltzmann Constant, ε is the material emissive constant, and T_h and T_c are the absolute temperatures of the hot and cold surfaces, respectively.

For an anodized aluminum case with emissivity of 0.76 [6], we determined that the heat generated by the Picosat Beacon during steady-state operation could be completely dissipated by 216 cm^2 of aluminum. The heat generated by the Distributed Wireless Beacon emitter and controller units can be dissipated by 36 cm^2 of aluminum. The actual enclosure of the Picosat Beacon and Distributed Wireless Beacon has an aluminum surface area of 600 cm^2 and 70 cm^2, respectively. Thus, a basic analysis shows the distress beacon designs can adequately dissipate excess heat from the LEDs.

4.4 Wireless Performance

To verify the performance of the wireless link between the controller and emitters, we developed a test rig to approximate an astronaut inside a space suit. The test rig consisted of a large plastic bucket (19" x 13" x 15") filled with water, and wrapped in two layers of the aluminized Mylar, which is material used in space suits. A wireless transmitter was placed on one side of the test rig, and a receiver was placed on the other side. Next, a known number of packets were transmitted through the test rig, and the error rate was recorded. The total error rate was less than 1 dropped packet in 30, or 3.3%. Due to the low data rate required by our application, the risk of lost packets can be mitigated by simply transmitting all messages multiple times.

4 CONCLUSIONS

We developed and characterized two optical distress beacon prototypes for use by astronauts during EVAs. The Picosat Beacon is compatible with The Aerospace Corporation's current picosatellite architecture. The Distributed Wireless Beacon is a modular design consisting of a single controller unit capable of activating any number of emitter units.

Preliminary testing revealed that a green LED with a 5 Hz 20% duty cycle strobe, was most visible. Beacon prototypes include both green and red LEDs to alternate colors. Based on experimental testing, the Distributed Wirelesss Beacon is visible from 0.07 miles in daylight and 0.50 miles at night. The Picosat Beacon runs for 3.5 hours in strobe mode and 1.3 hours in S-O-S mode. Similarly, the Distributed Wireless Beacon rubs for 31 in strobe mode and 12 hours in S-O-S mode. Each prototype is capable of radiating excess heat from the LEDs.

Future work includes a link budget to predict visibility against celestial objects, such as the moon, sun, and earth. Alternate light sources, such as xenon lamps, and light focusing methods should be explored to improve beacon visibility. Lastly, the distress beacon prototypes are capable of automatic triggering. However, further integration with health sensors is needed. Depending on the type of emergency, the beacon could be programmed to transmit different signals.

ACKNOWLEDGEMENTS

This work was performed as a Harvey Mudd College Engineering Clinic and supported by The Aerospace Corporation's Corporate University Affiliates Program.

References

1. "Cospas-Sarsat System Data." Cospas-Sarsat. Montreal: Cospas-Sarsat Secretariat, 2007.
2. Love, Stanley G. Astronaut. Telephone interview. 10 Mar. 2008.
3. Graham, C. H., and H. K. Hartline. "The Response of Single Visual Sense Cells to Lights of Different Wave Lengths." *The Journal of General Physiology* Vol. 18, 917-931. 1935
4. "Picosats Snap a Shot of Discovery". The Aerospace Corporation. Press release. Retrieved on 2008-04-18. December 20, 2006.
5. "LM3405 1.6MHz, 1A Constant Current Buck Regulator for Powering LEDs." National Semiconductor. 2007.
6. "Material Emissivity Properties." Electro-Optical Industries, Inc. 2000.