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OLED Technology Evaluation for Space Applications

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Abstract

This paper discusses a comparison of active matrix organic light emitting diode (AMOLED) display technologies against conventional active matrix liquid crystal display (LCD) technologies for use in environments associated with crewed deep spaceflight missions. LCD based and organic light emitting diode (OLED) based display technology discussion centers around non-space flight characteristics such as reliability, image and video performance, and display color temperature stability in addition to unique space flight characteristics such as radiation tolerance, thermal vacuum performance, display surface optics and material considerations. The focus of this paper is to highlight steps taken in attempting to understand which characteristics are of particular significance as applied to the emerging OLED display technology, in addition to brief market considerations of when, and if, OLED could be the right solution for display use in crewed space flight missions.

Nomenclature

°	=	degrees
”	=	inches
C	=	Celsius
F	=	Fahrenheit
FC	=	Foot Candle
fL	=	foot-lambert
G	=	gravitational acceleration
HP	=	horizontal polarization
L	=	luminance
L_{max}	=	maximum luminance
L_{min}	=	minimum luminance
MeV	=	mega electron-volts
psi	=	pounds per square inch
psia	=	pounds per square inch absolute
rad	=	radiation absorbed dose
RGB	=	red, green, blue
Si	=	silicon
T	=	temperature
u’	=	chromaticity coordinate (horizontal axis)
v’	=	chromaticity coordinate (vertical axis)
VP	=	vertical polarization

I. Introduction

Displays are a critical part of the avionics system for crewed spacecraft, as they provide the crew with an integrated and easily comprehendible picture of all aspects of spacecraft status, such as navigational information, vehicle health, procedures and checklists. Traditional unmanned spacecraft design emphasizes minimizing size, weight, and power (SWaP) of vehicle subsystems. When humans are introduced into a spacecraft system, it becomes necessary to consider many additional factors relevant to the humans, in addition to the previously mentioned factors similarly considered for an unmanned system. One significant consideration in a human rated system is how displays will be used to communicate information to the flight crew. The limited volume and limited humanly accessible surface area suitable for communicating important visual information to the crew places a premium on the multiple roles displays need to fulfill for future spacecraft, and this aspect is briefly discussed in this paper. Spacecraft display systems have evolved from a few small monochrome displays in historic spacecraft cockpits to complete "glass cockpit" configurations, in the most recent spacecraft cockpits. The most recent spacecraft cockpits include several large, full color digital electronic displays. As spacecraft display systems continue this evolution, their increasing resolution and size options will provide improved system awareness to the crew. Reduction in SWaP, as well as enhanced reliability and superior optical performance of the newer display technologies, have enabled new display capabilities, expanding their role in spacecraft avionics systems.

Digital electronic displays have been a part of human space missions from the Space Shuttle to the Orion capsule design that is currently under development. Having flown for almost 30 years, the Space Shuttle provides an excellent example of how display systems have evolved in this timeframe. The initial Space Shuttle display system used four 5" x 7" Cathode Ray Tube (CRT) displays that supplemented an array of sophisticated electromechanical instruments. These displays were multifunctional and allowed the crew to navigate via keypad interfaces to various pages of information on the four display units. During the 1990's, the Space Shuttle was retrofitted with eleven 6.7" x 6.7" high contrast, sunlight readable Liquid Crystal Displays (LCD). These eleven LCD displays replaced 32 gauges and electromechanical instruments, as well as the four original CRT displays, resulting in significant savings in weight and power. Space applications have unique and challenging environmental requirements that include: vibration, radiation, thermal extremes, vacuum, shock, sunlight readability, and micro gravity.

Recently, significant advances have been made in a new Organic Light Emitting Diode (OLED) display technology, which are enabling revolutionary advances in consumer electronic products ranging from smart phones with premium display image quality (e.g., wider viewing angles, superior color gamut and contrast ratio and high speed video performance) and very low power consumption, to large size premium performance televisions (TVs), to very thin and light-weight flexible (unbreakable) displays. When compared to LCDs, OLEDs offer superior SWaP attributes, image and video performance, temperature independent video image quality, and have a potential to be next generation display technology for Space applications. A detailed evaluation of the OLED display technology has been conducted, and the performance of representative state-of-the art OLED displays has been tested against various manned space mission environmental requirements, both natural and induced. These studies included optical performance testing over extended temperatures (e.g., -40°C to +70°C), electromagnetic compatibility (EMC) testing, thermal vacuum (TVAC) testing and radiation testing. The TVAC testing included tests at habitable pressures, TVAC cycling, and rapid depressurization tests, and the results are discussed herein. Limited EMC radiated emissions (RE) and radiated susceptibility (RS) testing was conducted in accordance with International Space Station (ISS) EMC requirements and those results are also discussed. Finally, radiation test results for the low earth orbit (LEO) environment are shared in the paper.

Based on the results from these studies and testing, this paper compares the active matrix OLED display technologies against the current active matrix LCD technologies for use in environments associated with crewed deep spaceflight missions. LCD based and OLED based display technology discussion centers around non-space flight characteristics such as reliability, image and video performance, and display color temperature stability, in addition to unique space flight characteristics such as radiation tolerance, TVAC performance, display surface optics and material considerations. The paper identifies two key points. First, it highlights steps taken to understand which characteristics are of particular significance as applied to the emerging OLED display technology. Second, it addresses market considerations, which determine when, and if, OLED display technology could be the right solution for display use in crewed space flight missions.

II. Role of Displays in various Space Missions

Human-rated spacecraft are more complex than unmanned spacecraft. For non-autonomous or semi-autonomous spacecraft, the crew may be required to monitor system status and issue appropriate control commands to spacecraft systems based on situational conditions. The crew's mental model, or "situational awareness" of the spacecraft's condition is influenced by their ability to gather and cross check a variety of visual indicators from onboard systems aligned with information provided by flight controllers. The crew must make sound decisions regarding how to proceed during routine operation of the spacecraft and during times of high stress when dealing with anomalous conditions that threaten the mission or crew safety. The exact means for the crew to gather the visual information that leads to situational awareness has changed significantly from the Gemini and Apollo era and further through the Space Shuttle and ISS era. The methods will continue to change as technology influences new ways to accomplish this task in ways that benefit the human element. The following discussion illustrates a progression towards the use of modern displays pertaining to the human space program.

The displays used in the earliest space programs (as illustrated in Fig. 1) such as Gemini and Apollo were very different from today's displays. For the early programs, the physical state of controls and specialized single-purpose instrumentation comprised the visual feedback for the crew. For example, the crew's ability to visually interpret the configuration of various toggle switches, rotary selectors, backlit lens covers with fixed alphanumeric messages along with electromechanically driven dials, gauges, and indicators was necessary for them to then formulate appropriate commands to effect a spacecraft's correct configuration.

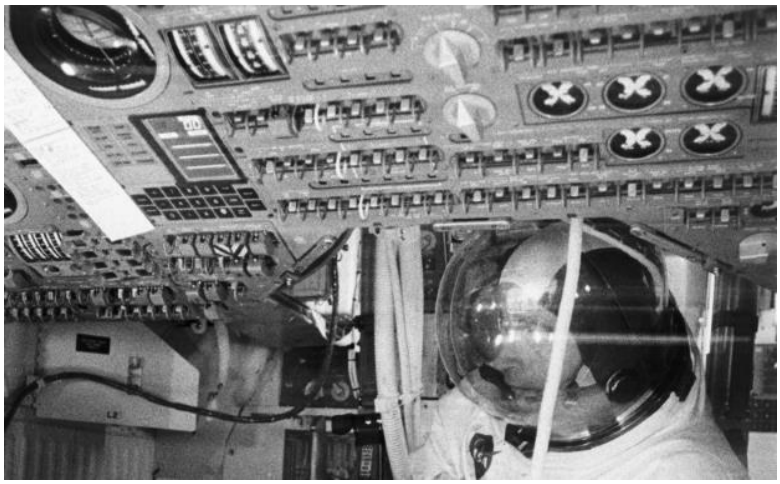

Figure 1. John W. Young working in the Apollo 10 Prime Crew Command Module.

Even the display of information from sophisticated instrumentation was visually communicated to crew via electromechanically driven instrumentation from the flight Attitude Director Indicator (ADI). Computers during this time were primitive by today's standards. Communicating data to crew consisted of backlit lens covers with fixed alphanumeric messages and electrically driven numeric gas discharge tubes that served to visually convey several digits of system status information from the computers. In order to make use of these few digits of information, crew were required to find the associated human interpretable message from a physical paper lookup table. Accommodation of all the physical components that provided this essential information to the crew was aggregated in consoles as the method that supported manned missions to the moon. This was a sufficient approach for the Apollo program because mission profiles were completed in brief, fixed durations and it was not expected that crew would use the console interface to do anything not related to the specific mission of flying to the moon and back.

Space Shuttle era vehicles shared similar means to monitor and control the state of the vehicle to that of the Apollo era, but were markedly different due to improved

Figure 2. Portion of Space Shuttle cockpit featuring two multi-color MEDS LCD display devices.

capabilities of computers utilized for the Space Shuttle program. As in the Apollo era, the Space Shuttle crew visually interpreted the state of toggle and rotary switches, electromechanically driven dials and gauges, and backlit lens covers to form part of their mental model of the commanded state of the spacecraft. Various special purpose navigational instrument displays were also included in the control panel for the purpose of providing visual navigation and guidance information to the crew during each flight phase. For example, displays of guidance and navigation information via the ADI or Horizontal Situational Indicator (HSI) to crew were accomplished via multiple single purpose electromechanical display heads that received inputs from the Space Shuttle's general purpose computers (GPCs).

However, unlike the Apollo era crew members who could only view a few digits of numerical information via numeric gas discharge tubes, Space Shuttle crew members reaped the benefits of being able to visually interpret data from multiple screens of monochrome, vector drawn alphanumeric information sourced from the vehicle's flight computers and displayed on several CRT devices. CRTs were also used for heads up display (HUD) by projecting data used for guidance and navigation onto a forward-looking window. Use of the HUD allowed the crew piloting the vehicle to monitor guidance and navigation information while looking out the forward facing window during critical approach and landing phases of flight. Later in the Space Shuttle program, an effort was made to modernize the cockpit by using eleven liquid crystal, flat-panel, full-color displays to replace four monochrome CRT displays, 32 gauges, and four electromechanical displays. This "glass cockpit upgrade" or Multifunction Electronic Display Subsystem (MEDS), as shown in Fig. 2, provided increased capabilities, reduced power consumption by 90 watts and decreased weight by 75 pounds. Use of color provided a significant additional dimension to communicate display content to crew (e.g., yellow and red indicators for caution and emergency situations, respectively). Additionally, various indicators were placed directly on the graphical instruments to eliminate the need for cue cards and the need to look up information in flight data files.

Both the Space Shuttle and ISS have benefited from a progression of technological advancements in the laptop computer field. These advancements involve improvements to the hardware used in the construction of laptop displays as well as to the laptop's computational ability and network capability. For example, the very first laptop computer display used in the Space Shuttle program utilized a monochrome plasma discharge panel for the display. When laptops with thin film transistor (TFT) LCDs became a common feature of laptop computers, the Space Shuttle program was able to identify such commercial laptops suitable for use in low earth orbit (LEO). Rapid increases in computing power and increased network capability made it possible to begin mixing the function of viewing vehicle telemetry with more socially oriented functions in ways not previously possible. For example, Space Shuttle crew utilized laptops to communicate with terrestrially bound personnel via email and to exchange files. Technological growth in laptop capability made possible the bidirectional exchange of audio and motion imagery used for training, medical consultations, or even just for some face-to-face family time. At the extreme end of performance, laptop computers and their displays were utilized for performing 3D visualization and simulation of Space Shuttle flight activities in order to maintain crew proficiencies related to approach and landing of the vehicle.

The Space Shuttle primarily utilized CRT based display devices to monitor various Closed Circuit Television (CCTV) cameras mounted in distinct points around the vehicles. Specialized CRT based monitors simultaneously displayed information regarding a selected camera's telemetry overlaid on the CCTV motion imagery. This combined motion imagery and camera telemetry provided feedback regarding configuration of CCTV cameras used to monitor extravehicular activities (EVA) operations using the Space Shuttle's robotic arm. Initially, the ISS program did not share a similar need to view external motion imagery so it had no displays for this purpose. EVA operations on ISS were performed while docked with the visiting Space Shuttle and the Space Shuttle's ability to display motion imagery external to the ISS was essential for conducting ISS EVA activities. Though the early ISS lacked the ability to display external video, the Russian provided Service Module contains two fixed position CRT based displays that assist with docking of visiting resupply vehicles. With the addition of the Robotic Workstation (RWS) to ISS, it became possible to display video from the ISS video distribution system and thus to monitor use of the ISS robotic arms or to monitor crew during EVA activities. Motion imagery from the ISS CCTV is displayed on three LCD flat panel video monitors located in the RWS. The RWS as shown in Fig. 3 also utilizes a laptop and its associated TFT LCD display to visualize planned and actual motions of the ISS robotic arm in addition to providing access to view ISS telemetry and configure other systems that are a part of the ISS vehicle.

Figure 3. ISS Robotics Workstation utilizing LCD video monitors and laptops.

It is difficult to predict the application of technology in the far future of human space travel. Clearly, technologies to integrate modern LCD and/or OLED panels are in store for human space programs within the next 10 years. Future spacecraft will likely have a limited habitable volume which constrains the amount of surface area suitable for incorporation of displays. In such situations, multipurpose displays represent a potential benefit over fixed purpose displays. Multipurpose displays in this context refers to display technologies suitable for conveying visual information from a plethora of spacecraft systems including systems that: report telemetry, facilitate control of the spacecraft, and provide a means to display both still and motion imagery. The viewable content of the display may be re-defined without making physical changes to the vehicle hardware. This trend towards multipurpose displays is evident when discussing how displays and their use to control vehicular systems progressed from the Space Shuttle era to the Space Station era. Displays on ISS evolved to accommodate a changing vehicle whereas systems on the Space Shuttle remained relatively fixed. ISS accommodated control of systems via applications operating on laptop computers that could be modified by changing the laptops' software loads. Addition or modification of a Space Shuttle system required the addition of new display hardware, or physical changes to vehicle systems to allow for addition of displayable content to existing display infrastructure. Following the ISS example to its extreme, it is not difficult to imagine that in future space systems, display technology used in the configuration and control of space systems may be entirely mobile and always within arm's reach of crew. However, there clearly remains a need for some displays to remain in fixed locations for certain types of crew activities such as piloting a vehicle. Additionally, there still may be a reason to preserve individual physical controls and their associated visual cues indicating their state for essential functions (e.g., circuit breakers, backlit buttons and individual indicator). However, in many cases functions previously served through fixed dedicated instrumentation and physical controls can give way to elements defined within a multifunction display driven by modern networked computers.

Future spacecraft will use multifunction displays as a means for communication in addition to control and monitoring space systems telemetry. Crews on extended multiyear missions will want to maintain contact with friends, family and ground controllers. Crew member psychological needs will be helped by viewing video messages from family, and the displays will be used for training as well as interactions during medical consultations. Crew entertainment is another role that can be incorporated into a multifunctional display. Displays will become more significant in EVA; EVA helmet HUDs, surface habitats and rover assessments.

In summary, history of display use in the space program has demonstrated a progressive aggregation of display functionality. This progression has been made possible by the development of modern display technologies and accompanying growth of compact computational resources. Earliest space programs did not have displays in the terms that we consider today. Display functionality was limited to the visual cues from physical controls such as rotary selectors and toggle switches combined with electromechanically driven display devices. In the Apollo era, early computers took us to the moon and communicated to the human element via a few numerical digits driven to gas discharge tubes. Space Shuttle era vehicles saw the rise of the CRT as a primary display device for communicating with vehicle computational resources, and this later gave way to the LCD based display. The Space Shuttle experienced a significant aggregation of display elements such as visual cues from physical devices and a number of electromechanical display devices into TFT LCD displays. All the while, growth of laptop computing and display technology brought another layer of aggregation of function to spaceflight crews. The next 10 years will see spacecraft using LCD and OLED technology. Future space missions will see efficient display technology that serve not only flight spacecraft but also habitats, EVAs, and surface rovers, spacecraft command and control as well as a myriad of other activities to enhance crew situational awareness, and crew physical and psychological health and readiness. To prepare for this advancement in display technology for space, it is necessary to understand the optical and environmental performance characteristics in the target environment, and make a comparative assessment of LCD and OLED technologies.

III. Display Technology Requirements for Space Applications

Typical, present-day display performance requirements, as specified herein, are predicated on a specific viewing position. This, in turn, is based on the space capsule design. The crew's nominal azimuth and elevation angles, when seated and looking at the display, represent the eye reference point, or design eye point. Looking at the display from an azimuth of 0° and a downward angle of 15° would produce a design eye point of (15°, 0°). However, when a generic display is measured in the lab, and there is no known design eye point, measurements are collected normal to the screen center; 0° azimuth and 0° elevation, or (0°, 0°).

A. Optical Performance

OLED displays for space must meet or exceed the optical requirements for LCDs. The first application for LCDs in space was the MEDS for the Shuttle. Currently, LCD displays are being developed for numerous space applications. The following are considered minimum optical requirements.

1. Optical Performance at Environmental Extremes

Detailed optical performance is usually measured under controlled conditions, where the temperature is controlled to room temperature and the ambient lighting is completely dark. Even over temperature extremes the display must be useable. Visual evaluation is performed at the environmental extremes to ensure the display symbology is readable with no erroneous interpretation. It is difficult to test every unit over temperature, so typically a representative unit is tested. The measured performance results are then applied to all like displays. In a situation where a number of production displays will be made, sample testing of pre-production displays is usually performed, and the production performance limits are established by statistical analysis of the sample display tests. Temperature range is typically from -25º C to 65º C. Units are sampled over temperature to assure that units passing the room temperature requirements support the extended temperature range.

2. Display Chromaticity

The display chromaticity coordinates[1] for red, green, blue and white are defined by the Tables 1 and 2, when measured from the design eye position. Color performance specifications can include specific viewing angle requirements imposed by a particular flight deck's design. That level of detail is not provided in this paper, since each flight deck design has its own unique requirements for customer specified viewing angles. The specified primary and white color targets provide very good saturated primary colors, in addition to a white value that matches the white used on commercial and business flight deck displays.

Table 1. Chromaticity at Design Eye Position.

Color	u'	v'
Red	0.385	0.540
Green	0.010	0.570
Blue	0.200	0.075
White	0.200	0.490

Table 2. Chromaticity Variance.

Color	Radius
Red	0.03
Green	0.03
Blue	0.08
White	0.03

3. Luminance

When commanded to maximum luminance, the average full screen maximum gray scale white luminance should be 100 fL. When commanded to minimum luminance, the average full screen maximum gray scale white luminance should be 0.1 fL or less. The 1000:1 dimming ratio is easily achieved with a space-based LCD. Whereas the same ratio is possible with OLED technology, the dimming mechanism for the two display technologies is quite different, and for now, the LCD is more easily able to meet the wide dimming range. In the LCD, dimming is controlled by the backlight. As the backlight brightness is varied, the display brightness can be increased or decreased with no appreciable color shift in the display. On the OLED display, the individual color dots are dimmed directly. To the extent that red, green, and blue change efficacy as the drive currents are modulated, the overall display appearance can assume color shifts which are not present in the LCD. This characteristic of OLED displays can be mitigated via compensation, however, as discussed in a later section of this paper.

4. Contrast Ratio

Dark ambient contrast ratio of the display unit should be greater than 100:1 at the design eye position. Dark ambient contrast ratio of the display unit should not be less than 20:1 when measured within the viewing envelope.

High ambient contrast ratio of the display unit should be greater than or equal to 3:1, when measured at the design eye position with the ambient illumination incident at an angle of 45°. High ambient illumination is defined to be 5000 FC diffuse illumination.

5. Luminance Non-Uniformity

Luminance non-uniformity is calculated using the equation below, and all luminance non-uniformity measurements should be made in dark ambient conditions with room ambient illumination less than 0.1 FC incident on the display surface, at an angle of 0° horizontal and 0° vertical relative to the display surface. Large area luminance non-uniformity applies to the color of white; Small area background luminance non-uniformity applies to the color of black. Where L_{max} is the maximum luminance measured on the display screen and L_{min} is the minimum luminance on the screen.

$$Non - Uniformity = \frac{L_{max} - L_{min}}{L_{max}} * 100\%, \quad (1)$$

At any luminance level within the specified dimming range, the small area background non-uniformity for black should be less than 40%. At any luminance level within the specified dimming range, the large area non-uniformity for maximum gray scale white should be less than 40% when measured in accordance with the Information Display Measurements Standards[2] using a 9-point pattern and a measurement aperture of 0.5 +/- 0.125 inches in diameter.

6. Display Light Leakage

The display unit (DU) should exhibit no discernible light leakage over the standard display viewing envelope forward of the bezel housing. Light leakage is specific to LCDs, in that they employ a backlight which continuously emits light when the display is on. Depending how the polarizer films are applied to the LCD, and how the bezel is designed, LCDs can leak light at extreme viewing angles. In contrast, OLED displays only drive the pixels that are needed, and all unused pixels remain black. So, light leakage can theoretically be eliminated altogether for the OLED display.

7. Reflectivity

In operating environments where the display is shielded from direct sunlight illumination, a higher reflectivity can be tolerated than when the display is exposed to direct sunlight illumination. Displays mounted within the spacecraft in crew workspaces, on the flight deck, or in other spaces largely protected from direct sunlight illumination can perform well with less than 2.2% specular reflectance measured per MIL-L-85762, paragraph 4.8.16.2.3.2, and less than 0.25% diffuse reflectance measured per MIL-L-85762, paragraph 4.8.16.2.3.1. Low reflectivity is needed for good sunlight viewing performance. For extra-vehicular display locations, a specular reflectance less than 1% would be desirable. Boosting display luminance can also be used to offset the contrast reducing effect of direct sunlight illumination. Increasing an LCD's backlight power might be more easily handled than increasing an AMOLED's operating power to achieve high display brightness. The particular characteristics of a given AMOLED display's emissive materials and its mechanical package's ability to remove heat from the AMOLED emissive substrate would determine how much power increase could be tolerated to achieve higher display luminance. However, both display technologies are well suited to provide low reflectance and high luminance under direct sunlight viewing conditions.

8. Long Term Image Retention

No long term image retention is allowed. Image retention presents itself as the ghost image of a previous display format whereas a different display format is being displayed. Aside from being annoying to look at, image retention makes it difficult to discern and focus on the current display data. The mechanisms for creating image retention are different for the two display technologies. After much development effort, image retention phenomenon in LCDs is well understood and the image retention issue is resolved under most practical ambient operating conditions including those associated with space. However, currently OLED technology is not nearly as mature with respect to tolerance to image retention under stringent conditions of high operating temperatures and static long duration symbology.

9. Response Time

The display should be capable of transitioning from any gray level to any other gray level within 17ms within 10 minutes of power application at the cold temperature extreme. Response time versus ambient temperature is a unique performance limit for LCDs; OLED displays are quite insensitive to cold temperature. Liquid crystal material becomes more viscous and less responsive at cold temperatures, thus the slow response time. If a dynamic image is shown on an LCD at -40°C, the image will move very sluggishly. As the liquid material warms, its response time improves, and the image quality will improve substantially. The specification time from when power is applied to when the display is considered readable will depend on the system design, and is based on how long the displays can operate on batteries before they have to switch over to a different power source. OLEDs have response times in the microseconds; cold temperature performance is not a problem for them.

B. Environment Performance Requirements

Table 3 represents the typical display requirements for space applications.

Table 3. Typical display test requirements for Space Applications.

Environmental	Requirement
Operating temperature range	-25°C to +65°C
Ambient Pressure	Ambient pressure environment ranging from 1.93E-6 psi (1 x 10E-4 torr) to 15.2 psi (786.1 torr) for not less than 144 hours
Humidity	Humidity test in accordance with MIL-STD-810 method 507.4
Random Vibration	Composite of > 10 Grms
Acceleration	20 G constant acceleration for 5 minutes in each direction for each axis
Shock	20 G terminal sawtooth shock pulse of 11ms duration two times in each axis, as shown in Figure 30 (MIL-STD-810, method 516, procedure 1)
Ozone	Operate after exposure to 3 to 6 ppm, total oxidant concentrations may reach 60 ppm for 1 to 3 hours in any 24 hour period
Fungus	Operate after exposure to requirements specified in MIL-HDBK-454, requirement 4, Fungus Inert Materials, Table 4-I Group I
Sand & Dust	Operate after exposure to 140-mesh silica flour with particle velocity up to 500 feet per minute and a particle density of 0.25 grams per cubic feet (MIL-STD-810F, Method 510.4, Procedure 1)
Salt Fog	Operate after exposure to salt fog test per MIL-STD-810F, Method 509.4, with 4 alternating 24 hour periods of salt fog exposure and drying periods

IV. LCDs for Human Space Use

Spacecraft displays serve one purpose: convey important information to crew members on human space flight missions. Information importance is encoded into the size, position, movement, shape, update rate, and color of graphical elements presented on the display surface. Information importance can also be encoded in how much detail is provided for particular information content. For example, maps having fine resolution are needed for maneuvering a vehicle through a complex three-dimensional space.

Arranging complex and dynamic information into visual formats which can be readily and easily processed by the human visual system in the manned space environment is a particular challenge for human factors engineers. Severe vibration, operating temperature extremes, space suit visors, gloves, and the relative position of the viewer with respect to the display under weightless free-floating use, all factor into the optimum display format needed for those operating conditions.

A. LCD Media

Today's LCDs represent a refined and mature technology. Desktop-sized LCDs sporting 1920 x 1080 resolution at 60Hz and 24-bits of color resolution are quite commonplace, and they can be obtained at very modest cost. But this was not always the case. In 1994, LCDs with high resolution, wide color gamut, and wide viewing angle performance were almost non-existent. Add the harsh environmental operating requirements for avionics and space displays, and a rare product became a non-existing product.

To answer this need, companies Boeing, Honeywell, and Hosiden pioneered development of the first wide viewing angle LCDs suitable for an air-transport flight deck: Boeing's 777 aircraft. This same display technology was refined for manned space use in the NASA Space Shuttle flight deck. That display used the custom Red, Green, and Blue (RGB) delta triad pixel configuration. Today's displays use the RGB stripe pixel, which is an easier design to manufacture in high volume. The commercial display market has almost exclusively employed RGB stripe pixels for many years, now. Both pixel designs are optimized for the respective graphics architectures which provide data to the LCD module, and this aspect is discussed in a subsequent section.

At cold temperatures, LCDs exhibit slowed optical response, and a supplemental LCD heater is needed to provide acceptable LCD performance. Temperatures from -40°C to about +15°C require supplemental LCD heat. The heater imposes an additional burden on battery power systems, adds system weight and complexity, and adds new system failure modes to account for.

Finding LCD manufacturers who will support avionics/space use of their displays is also a challenge. Some manufacturers refuse to participate in this market, and will decline such business if it is offered to them. Their focus is low cost, high volume consumer products, and they lack the desire or resources to support avionics/space based displays. Product liability, and the high degree of support often required of the Original Equipment Manufacturers (OEMs) who produce space-grade equipment is more than some suppliers are willing to undertake. There are several LCD suppliers, though, who do support this market very well.

B. Back Light System

Low optical transmission through the LCD requires powerful back light assemblies to achieve high display brightness levels. Back light drive electronics take space, create heat, and add system complexity and weight. Luminaire design for the back light may require large depth to get good luminance uniformity with a direct view back light. The direct view back light places the light source behind a diffuser, directly behind the LCD. An edge-lit back light places the light source along a display edge, and uses a light-guide plate and diffuser to uniformly distribute the light from the edge to the LCD's surface area. An edge-lit LCD may require less depth, but may not be able to provide the high luminance needed for direct sunlight viewing.

Historically, hot cathode fluorescent back lights have been used in high brightness display applications which needed a wide dimming range. But the display industry has largely migrated to LED backlights. Substantial improvements in LED performance, coupled with their mechanical robustness, low cost, wide supply base, and ease of driving them make them very desirable over fluorescent back lights. Most back lights today employ LEDs as the light source.

C. Graphics Generation and Image Quality

The graphics data provided to an LCD is matched to the display's pixel configuration. The LCDs used in the space shuttle employed the RGB delta triad pixel. These displays provided high optical performance that many commercial displays could only recently provide. The pixel design was matched to a patented graphics architecture so that the LCD produced CRT-like viewing characteristics, and high graphics processing throughput. The graphics architecture defined line profiles which possessed the Gaussian luminance roll-off provided by an electron beam on the CRT display. In spite of the LCD's fixed-size pixel array, graphical elements did not display the jagged, pixilated quality that can be observed on some LCDs to this very day. Instead, the graphics looked very CRT-like, that is, smooth and very easy on the eyes, and displaying no undesirable visual artifacts. This architecture also provided a very efficient way to create compressed graphics data outside the display, and transmit the compressed graphics on a high speed serial data bus to the display head, where the compressed image was efficiently and quickly decompressed and rendered. Commercial graphics processing units (GPUs) were not able to match the graphics throughput and rendering speed of this custom graphics/display architecture until many years after this custom system was designed.

Commercial LCDs were using the RGB stripe pixel layout, due to its simplicity and ease of driving. The RGB stripe was long ago standardized on the Personal Computer (PC) graphics cards, and its evolution continues to today. However, the RGB stripe pixels are prone to exhibit aliasing errors as graphical elements are moved and rotated across a display surface as part of a dynamically changing image. For example, if a circular engine instrument dial with a linear, rotating needle is observed, the needle will assume a ragged quality as the RGB pixels which produce the needle are programmed to produce the appearance of rotation. A vertical needle will not look the same as a needle when it rotates towards 90°.

V. AMOLED Technology Assessment

Active Matrix Organic Light Emitting Diode (AMOLED) displays offer the potential to be thinner and lighter weight than LCDs, as well as require less power. The OLED is self-emissive, and requires no backlight. It does require thermal management to channel heat away from the display to the chassis or to the ambient environment. In the following paragraphs, the thermal performance, chromaticity, viewing angle performance, and image retention are considered.

Two AMOLED display types are evaluated in this report: a 7.7" diagonal wide format display, and a 4.3" diagonal display. The optical performance data is based on the newer technology 7.7" commercial AMOLED display. The environmental test data is based on the 4.3" AMOLED display. Since excellent optical performance is one of the goals for a crewed space mission display, the newer 7.7" display was selected for optical performance reporting. This module offers a good sample point for state-of-the-art AMOLED optical performance. However, its mechanical packaging was less suitable for environmental tests than the 4.3" AMOLED display. For that reason, the 4.3" display was used for environmental tests.

Figure 4. AMOLED cold temperature startup.

A. Thermal Performance

Thermal performance advantages of AMOLED technology over LCD technology include cold temperature response time, and the performance of contrast ratio and color stability over operating temperature extremes. Color stability, in this context, means the appearance of primary colors at hot and cold temperature extremes. Primary color purity is more stable for the AMOLED; however primary color luminance for the AMOLED is not as stable over temperature as the LCD. Color mixes on the AMOLED display can show color shifts, but this shift results from the relative luminance changes of the primary colors, and not from a fundamental shift in the primary color.

Figure 5. LCD cold temperature startup.

At cold temperatures, the AMOLED display provides almost instantaneous performance (refer to Fig. 4), whereas the LCD requires some time to warm up; typically 8 minutes, with supplemental heat applied to the display. The LCD's liquid crystal material is a viscous liquid that becomes thick and sluggish at cold temperatures. The slow liquid crystal response at cold temperature produces dynamic images which appear to be at first static, then blurred and very sluggish before warming produces an acceptable dynamic image. A quickly moving dial needle, or a scrolling tape at cold temperature will appear smeared, and difficult to read as illustrated in Fig. 5. An AMOLED will produce full dynamic video performance at cold temperatures, since the AMOLED is self-emissive. OLED technology's disadvantage is color shift over the temperature profile. Since red, green, and blue emitters provide unique normalized luminance versus temperature profiles, the AMOLED display's color performance will vary over temperature, unless compensation is implemented to offset thermal performance changes (described below in D).

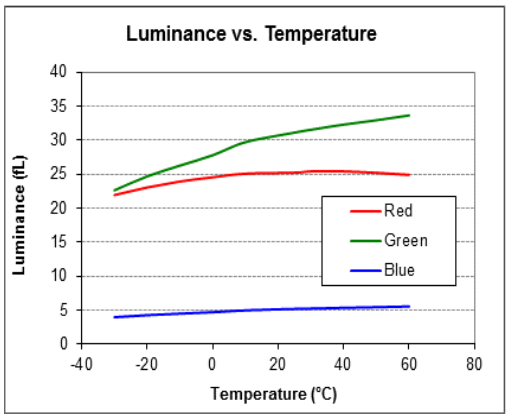

Figure 6. RGB luminance vs temperature, 100% Driven.

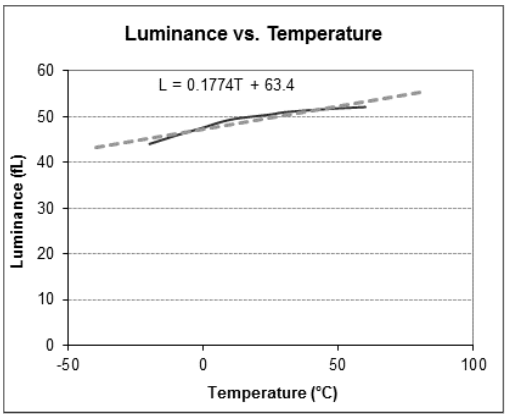

Figure 7. White luminance vs temperature, 100% Driven.

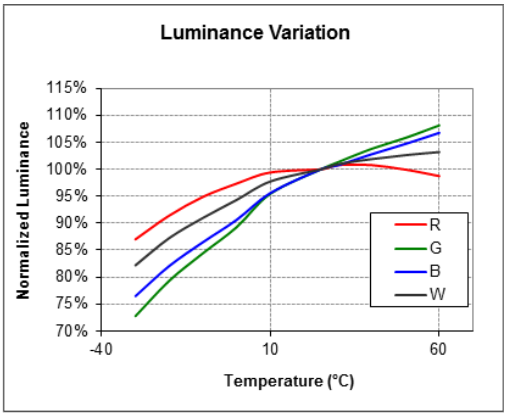

Figure 8. Normalized luminance variation vs temperature, 100% Driven.

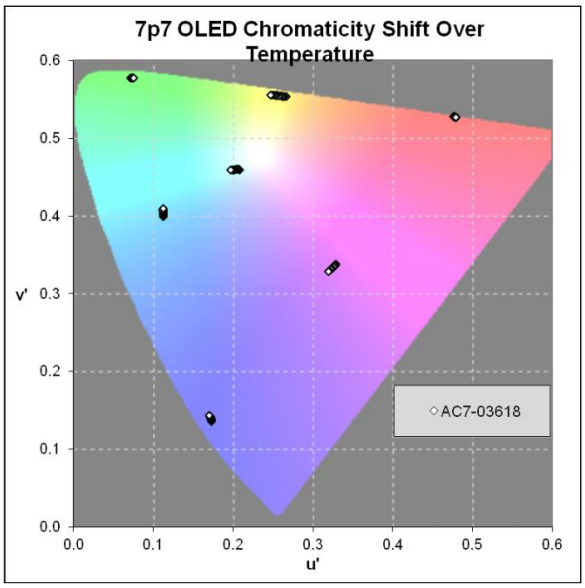

Figure 9. AMOLED chromaticity shift over temperature.

The Luminance versus Temperature plots shown in Figs. 6 and 7 exhibit smooth luminance changes over ambient operating temperature range. From Fig. 8, one can observe that the normalized temperature performance curves do not track between red, green and blue. These differences would produce color shifts over the operating temperature range while holding constant RGB drive levels. This effect can be seen in the chromaticity shift of the secondary colors in Fig. 9. For example if Red=128, Green=128, and Blue=128 are driven from the graphics generator to the display, then that shade of white would appear more reddish at cold temperature, and more cyan-like at high temperature. This is because the red has a stronger contribution at cold temperature, and a reduced contribution at high temperature, based on the normalized luminance profiles. The normalized curves also show that red has a slight downward trend at 60°C, whereas green and blue do not; they have increasing luminance with increasing temperature at 60°C. The blue and green curves also track differently relative to each other from one end of the temperature spectrum to the other. At high temperature, green maintains more of its luminance than blue, but at cold temperature, green loses more luminance than blue. A cyan color would appear more bluish at cold temperatures, and more greenish at high temperatures. Given an empirical model for these changes, the display system can compensate for thermal color shifts by changing the pixel drive, or by changing the programmed mixes of RGB in the operating software. Lookup tables can also translate software values to hardware values as a function of temperature.

B. Chromaticity and Emission Spectra

The 7.7" AMOLED possesses excellent chromaticity. For all tested temperature profiles, this OLED display provides a color gamut of 115% of the National Television System Committee (NTSC) color gamut. This compares quite favorably to the 70% to 75% NTSC color gamut provided by many LCDs. Figure 10 shows the room temperature chromaticity compared to the NTSC standard. Figure 11 shows the white emission spectra from -30° to +60°C. The AMOLED display provides red, green, and blue saturation levels which are very difficult to capture with a digital camera, but which can be easily observed by eye. Figure 9 shows the color shift versus temperature, demonstrating how the relative temperature performance of one primary color compared to alternate primary colors causes color shift. This shift is not due to intrinsic primary color shifts, rather it results from relative luminance changes over temperature.

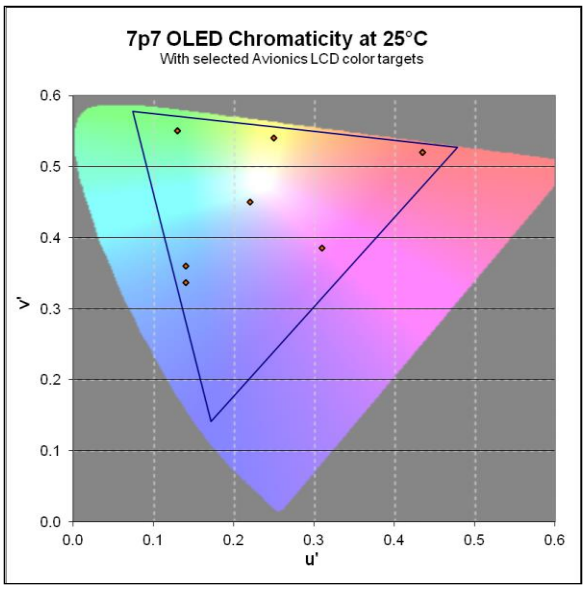

Figure 10. AMOLED chromaticity at +25°C.

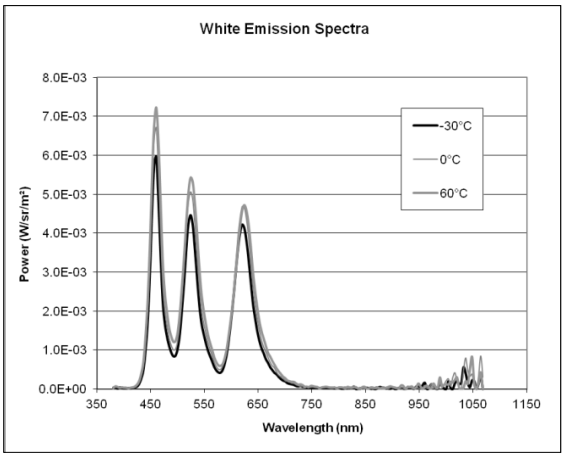

Figure 11. White spectra over temperature.

C. Viewing Angle

AMOLED technology provides exceptional and symmetrical contrast performance over very wide viewing angles. Figure 12 illustrates the constrast ratio over the viewing angles up to 60° in both the azimuth and elevation. Even at the most extreme viewing angles, the contrast ratio exceeds 4500. Luminance as a function of viewing angle for Gray Level 128 White is shown in Fig. 13. Individual primary colors possess similar performance for high, mid, and low gray levels.

D. Image Retention

Image retention occurs when a residual image of a previous display format is visible while the current and different display format is being presented. The characteristic is most likely to appear when static, or quasi-static images are displayed for protracted time periods. Instruments, dials, text, or other graphics may be present in the retained image.

Image retention has existed since the earliest days of cathode ray tubes, where long-term phosphor degradation produced ghost images on the display. This effect was prominent on oscilloscopes and computer monitors. LCDs ushered in new display technology, but still suffered from retained image; the underlying mechanism was new, though. Chemical impurities in the liquid crystal material caused direct current (DC) voltage biases to accumulate on the pixel, and this bias voltage contributed to retained image. Annealing the LCD at high temperature would free trapped charges, and reduce the retained image, but the benefit was only temporary, as static operating conditions would once again produce the retained image. As liquid materials became more chemically pure, image retention became much less prevalent in LCDs. Although image retention is substantially reduced in LCDs, it still exists.

AMOLED displays represent the third wave in display technology, and they too, can suffer from image retention. AMOLED displays, being self-emissive, share some characteristics with phosphor-based displays: material wear out, and differential aging. AMOLED displays produce light by passing current though the OLED material. When the material is new, the conversion efficiency is highest, and a fixed current produces a maximum amount of light. As the material ages, the conversion efficiency decreases, and the same amount of current produces less light. This, in turn, can be perceived as retained image.

Retained image can also be produced by the pixel bias voltages on an AMOLED display. Since the bias voltages are DC in nature, not alternating current (AC), the pixel transistors can acquire undesirable operating voltage biases, which detrimentally impact the pixel current. The effect is most prominent in amorphous silicon backplanes. The threshold voltage of amorphous silicon thin-film transistors changes under DC bias voltages, and this impacts the pixel current.

In AMOLED displays, it is possible to induce image retention with as few as several hours displaying a static, or quasi-static image. The extent to which image retention is accrued on an AMOLED display depends on the brightness level and the color. Dynamic images tend not to produce image retention. Static images can cause DC operating biases to develop in the active matrix array, which can influence the image retention behavior. Differential aging is the second performance attribute which contributes to image retention. Red, green, and blue emitter materials age at different rates. Generally, green has the longest life, followed by red, and then blue. Some OLED manufacturers design their pixel arrays to minimize the effects of differential aging by making the blue pixel area larger than red and green, and decreasing the blue pixel drive current. This provides the same blue intensity to the viewer while minimizing the effects of differential aging. Other manufacturers employ a white OLED with color filters. In September 2014, it was reported that LG Chemical produced an OLED lighting panel with 40,000 hour life[3] (twice as long a fluorescent lamp). Marrying this technology to color filters to make a display module would produce a display with similar life as an LCD. Balaganesan reports red phosphorescent emitter lifetime exceeding 44,000 hours[4]. Universal Display Corporation reports light blue emitter lifetime of 20,000 hours, green lifetime of 400,000 hours, and red lifetime varying from 250,000 hours to 900,000 hours based on the red color point, at continuous operation[5]. As the constituent primary colors age at different rates from one another, fixed color mixes will shift in color as their primary color components follow the respective aging profile. Cyan colors will become more greenish as the display ages. Amber colors will also become more greenish with age. Magenta will become more reddish with age, and whites and grays will shift towards a greenish hue with age.

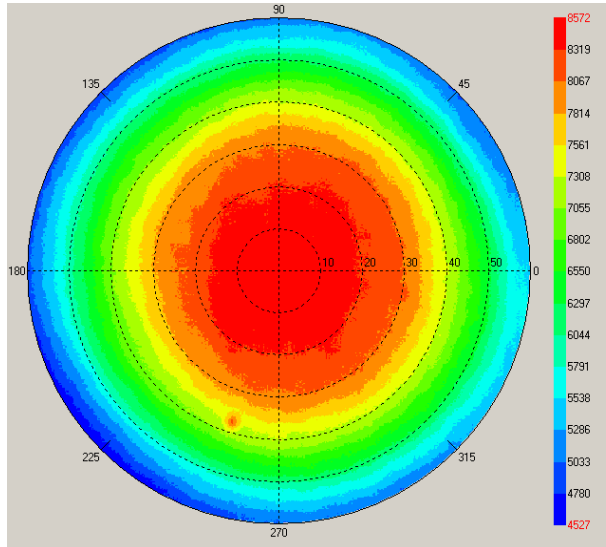

Figure 12. Contrast ratio over viewing angle.

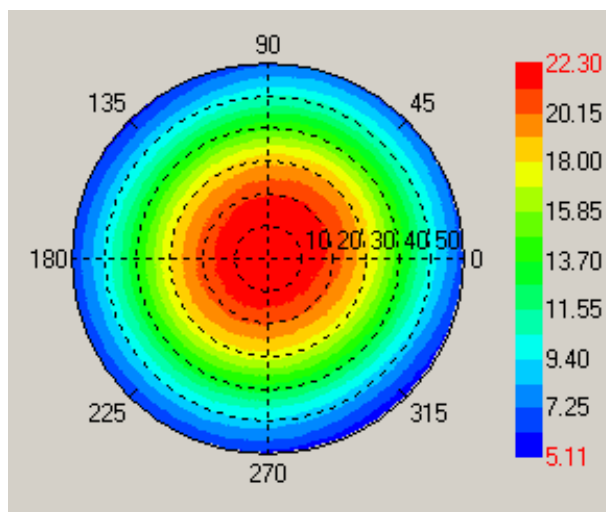

Figure 13. White gray level 128 luminance over viewing angle.

This effect can be offset, to some effect, by compensating the drive level of the aged colors. As the display accumulates operating hours, the green and blue components of a cyan color mix can be proportionately increased to account for the aging profile. This technique has an upper limit where such compensation is viable. For example, a new display might use Red=00, Green=96, Blue=96 for cyan. When the display has 8,000 hours on it, the new cyan color mix might be Red=00, Green=110, Blue=156 to achieve the desired color target.

The OLED industry is working aggressively to increase emitter life, balance the lifetimes of respective emitter materials, and compensate for differential aging to acceptable levels for premium performance applications.

E. Environmental Performance Testing

As part of the OLED technology investigation and to assess its suitability for space applications, two AMOLED displays (model numbers AZAMOLED043A (non-touch screen) and AZAMOLED043A-T (touch screen) by AZ Displays, Inc.) were subjected to three types of space hardware environmental testing: electromagnetic interference (EMI), TVAC, and proton radiation susceptibility. These tests are typical of a subset of screening activities performed at component and system level to determine their suitability for space applications or whether hardware modifications can be made for use in space. Environmental screening testing—a phase of development that typically takes place in a project's development cycle—for components where there has not been a plethora of accumulated experience (especially for spaceflight beyond LEO) is extremely prudent in the case of OLED panel displays as a relatively new display technology becoming available in display sizes attractive for use in future spacecraft cockpits.

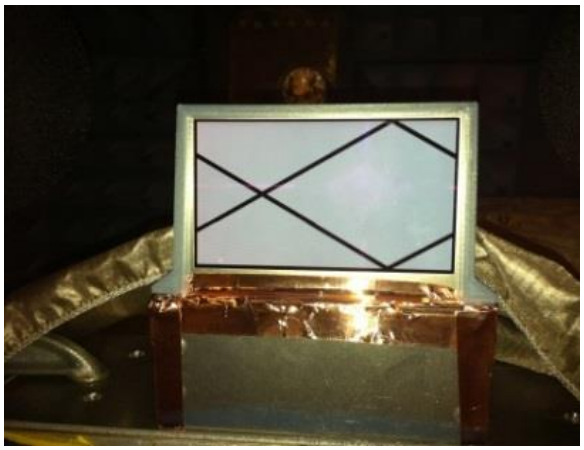

Figure 14. AMOLED test pattern.

The touch screen model was subjected only to EMI testing. It served as a backup test article to the non-touch screen. The non-touch screen display was subjected to all three tests. Before and after each test, the AMOLED display was characterized by measuring spectral and luminance characteristics to ascertain any permanent degradation in optical performance as a result of being subjected to the induced environment. Test personnel visually monitored each display for performance degradation or transient-type anomalies induced by the test. Also, the display was video recorded for later review in case an anomaly was overlooked during the test.

For each of the test environments, the display was driven by a test pattern comprised by a solid white background with a repeated "X" pattern slowly moving from right to left (as seen by an observer viewing the screen) and is shown in Fig. 14. The display pattern was provided to the device under test via laptop computer through a High Definition Multimedia Interface (HDMI) cable. This pattern was selected because it required activation of most of the OLED sub-pixels operating at 100% of their maximum illumination (i.e., white requiring fully illuminated red, green, and blue pixel sub-elements). This near 100% duty cycle condition was chosen because it was anticipated these conditions would provide the most stressful condition for the OLED pixel elements as well as the underlying thin film transistor structure used to supply drive current to the OLED. The moving "X" pattern offered a means to monitor for frozen screen artifacts, induced transient pixel activations (colored sparkles), or pixels stuck in an illuminated condition), and was provided during the test. The white area was monitored for induced transient pixel deactivations or pixels stuck OFF (unilluminated condition).

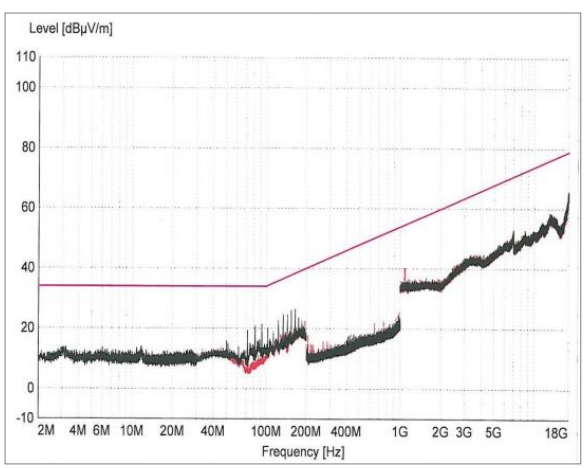

Figure 15. Radiated emissions 102 acceptance threshold.

1. *Electromagnetic Interference Testing*

EMI testing for the displays was broken down into two tests: an EMI radiated emissions (RE) test (electromagnetic radiated noise of the device under test) and EMI radiated susceptibility test (caused functional malfunctions to the device under test). For the EMI emissions test, both the touch screen and non-touch screen displays were subjected to radiated emissions testing (RE102), in accordance with the Military Standard 461F specification for radiated emissions 102 (MIL-STD-461F-RE102). For the radiated emissions testing, the display unit with the touch screen was modified by grounding the conductive thin film layers to chassis ground (essentially disabling the functionality of the touch screen). The thought was to observe whether there were any differences in

EMI emissions characteristics that might be attributed to the inclusion of a touch screen's conductive layers. In practice, no appreciable difference occurred in EMI emissions performance for either the touch screen unit or the non-touch screen unit. Figure 15 illustrates the measured radiated emissions levels for both units, which were for the radiated emissions test, and shows those levels measured over the frequency range from 2 MHz to 18 GHz. Both units' emissions were well under the MIL-STD-461F standard electromagnetic radiated noise threshold level for RE102 compliance, indicated by the red line.

Table 1. EMI Radiated Susceptibility Test Results.

Frequencies and Polarization	Test Results for Horizontal Polarization (HP) / Vertical Polarization (VP)
30-200 MHz (HP/VP)	Pass / Pass
200-1000 MHz (HP/VP)	Pass / Pass
1-2.5 GHz (HP/VP)	Pass / Pass
2.5-7.5 GHz (HP/VP)	Pass / Pass
7.5-18 GHz (HP/VP)	Pass / Pass

For EMI radiated susceptibility, only the non-touch screen display was tested against an abbreviated ISS radiated susceptibility 03 (RS03) specification (test frequencies known to cause problems with ISS electronic hardware) for radiated immunity, at three differing electric field intensity levels: 20, 50, and 75 volts per meter. Frequencies and polarization of the antenna and associated test results, where HP = Horizontal Polarization and VP = Vertical Polarization, are shown in Table 4. In all three electric field intensity environments, the AMOLED operated nominally with no anomalies detected. Post-EMI test optical characterization showed no degradation of the display.

2. Thermal Vacuum Testing

For TVAC testing, three environmental test profiles comprised by variable temperatures and pressures were examined: habitability pressures, thermal vacuum cycling, and rapid depressurization. For habitability, the test shows how well the display operates in pressures that the crew would experience. For TVAC cycling, the test is indicative of a temperature profile at each pressure to which a display would be subjected for workmanship screening. The rapid depressurization test was intended to confirm workmanship of the display as well as determine how well the display would operate if the crew cabin suddenly depressurized.

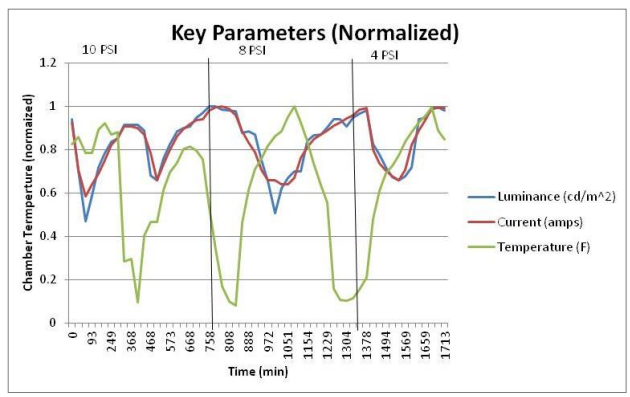

Figure 16. Current draw as a function of temperature.

Measurement data were captured for the AMOLED current draw, key circuit component temperatures (via thermocouples), spectral irradiance, colorimeter, and luminance for all the tests. The habitability test occurred at room temperature for 10, 8, and 4 psia, which are nominal pressures astronauts experience in the spaceflight environment. The display experienced no issues or anomalies throughout all habitability pressures. Next, one thermal cycle was performed from -20°F (-29°C) to +120°F (+49°C) at each of the habitability pressures (8, 10, and 4 psia). During these tests, it was noted that the display intensity decreased in conjunction with current draw at all habitable pressures as the chamber temperatures dropped. Also, the display color temperature shifted as the chamber temperature changed on both the cold cycle and the hot cycle, as shown in Fig. 16. The chamber was taken down from 14.7 to 0 psi at 1 psi/minute and then 2 psi/minute. In both cases, the display did not experience any electrical or mechanical issues. Table 5 lists the post-thermal optical characterization and indicates no lasting degradation of the display.

Table 5. Before and after thermal test optical performance.

Thermal Testing	Before	After
Average Luminance cd/m^2	144	150
CCT (K)	8148	8464
Chromaticity (x,y)	0.280	0.2777
	0.345	0.339
CRI	82	80

3. Radiation Testing

Proton radiation testing was conducted at the Indiana University Cyclotron Facility using their 200 MeV proton beam. The non-touch screen AMOLED display was radiation tested to 600 rads(Si), which is equivalent to a 10-year total dose inside the ISS, and then to 6,000 rads(Si), which is equivalent to a 10-year total dose outside the ISS. The AMOLED functioned nominally up to 600 rads(Si) giving an expected mean time between failures of better than 10 years. However, testing out to 6,000 rads(Si) showed permanent display degradation in terms of reduction in current draw and darkening of the display as it reached 6,000 rads(Si). Figure 17 shows the display after the radiation test. A lead brick covered a portion of the bottom of the screen, protecting it from the high-energy protons. This protected area is evident on the display. Efforts to thermally anneal the display did not correct the darkened screen; the screen remained permanently damaged.

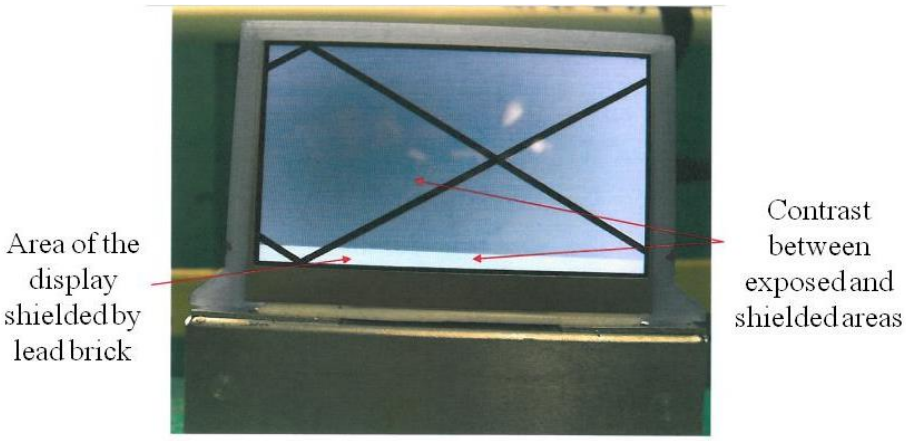

Figure 17. Display after proton testing to 6,000 rads(Si).

VI. Physical and Functional Improvements Recommended for the Use of AMOLED in Space Platforms

Table 6 shows a comparison of AMOLED display technologies against LCD display technologies. Whereas AMOLED technology appears to promise advancement in display capability for spacecraft, additional improvements regarding certain aspects warrant examination (e.g., most of the commercially available OLED displays are either too small, or too large, to be viable for use as cockpit mounted displays, as the commercial OLED industry is targeting the currently highly profitable products namely, high performance smart phones and high performance large area TVs). These displays should be in the neighborhood of 12” to 20” to offer effective display real estate for a cockpit. Other potential uses for AMOLEDs in space platforms, where size may not be so much of an issue, include helmet mounted displays for spacesuits, incorporated into windows as HUDs, or mobile devices that crew members could utilize at any location inside a cabin or habitat, or while on maneuvers. Additional improvements might include the incorporation of resistive touchscreens (capacitive touchscreens depend upon modified gloves or ungloved hands, which could limit their effectiveness in space), combining touchscreen with tactile/haptic/audio feedback (not necessarily on the screen itself), and architectural choices that enable the integration of displays into a multi-processor, redundant processing environment.

Table 6. Comparison of AMOLED display technologies against LCD display technologies.

	LCD	OLED
Optical	Mature	Mature, better color saturation
Luminance	Mature and can always increase by applying more power to the backlight	Mature, but limited by OLED Technology, which continues to make rapid progress
Thermal	Mature	Mature
Vibration	Mature	Mature, no cell gap issues like LCDs
Other Environments	Mature	Mature
Radiation	Mature, but components around LCD must be tested	More evaluation is needed, and components around OLED must be tested
Reliability	Mature and proven history in Space	Industry is rapidly improving operating life. Still testing in Space environments.
Weight	Acceptable	Offers weight reduction and shallower display depth, via the removal of the backlight and associated heat sink.
Power	Acceptable	Offers power reduction with the removal of backlight.

VII. Conclusion

AMOLED technology has made impressive advancements in lifetime and environmental robustness. The benefits of low power, light weight and thin size combined with excellent optical performance present compelling reasons to consider this technology for human space missions.

For display brightness levels in the vicinity of 120 fL, the AMOLED display may be a suitable candidate for human space use. For extremely bright displays requiring 200 fL, and very long lifetimes, currently an LCD may be a better choice. At extremely high brightness levels, the OLED display suffers from emitter life degradation and from thermal management challenges, particularly for long duration operation at high luminance levels. But for moderate brightness levels, the AMOLED display presents compelling performance attributes.

Although the AMOLED display used for the environmental performance testing was designed for commercial/industrial applications, it performed well during the EMI testing. However, the TVAC testing indicated the display is sensitive to temperature. Therefore, keeping the display within a controlled operating temperature range is important to ensure luminance and color shifts are minimized, particularly for displays that use color to convey information. It is also possible to design temperature compensation into the OLED drive electronics; such that, as the ambient temperature varies, the display dynamically modifies red, green, and blue drives to reduce color shifts over temperature. For LEO, proton radiation testing showed the display is suitable for use inside a spacecraft where the total dose does not exceed 600 rads(Si). However, if used externally, the display will begin to darken as the total dose exceeds 600 rads(Si) and thus permanently affect its optical properties. Heavy ion tests must be done to determine operability of OLED technology for beyond Earth orbit since that radiation environment is more severe than that of LEO.

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References

[1]"Colorimetry - Part 5 -- CIE 1976 L*u*v* Color space and u', v' uniform chromaticity scale diagram," *ISO 11664-5:2009 (CIE S 014-5/E:2009)*, Edition 1, International Standard Organization, 2009-12-01.

[2]"Uniformity Measurements", *Information Display Measurements Standard*, Version 1.03, Society for Information Display, Definitions and Standards Committee and International Committee for Display Metrology (ICDM), 2012, Section 8, pp., 134-137.

[3]Hwang, S. Y., "LG Chemical develops super-efficient OLED light panels," *CNET* [online newspaper], 2014-09-15, URL: http://www.cnet.com/news/lg-chem-develops-super-efficient-oled-light-panels/ [cited 15 June 2015].

[4]B. Balaganesan et al., "Progress on Phosphorescent OLED Materials," *Procedings of the 2015 SID International Symposium*, 28.3, Society for Information Display, California, 2015.

[5]"Features and Performance", *Universal Display Corporation* [online database], URL: http://www.udcoled.com/default.asp?contentID=604 [cited 15 June 2015].

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13. ABSTRACT *(Maximum 200 words)*
This paper discusses a comparison of active matrix organic light emitting diode (AMOLED) display technologies against conventional active matrix liquid crystal display (LCD) technologies for use in environments associated with crewed deep spaceflight missions. LCD based and organic light emitting diode (OLED) based display technology discussion centers around non-space flight characteristics such as reliability, image and video performance, and display color temperature stability in addition to unique space flight characteristics such as radiation tolerance, thermal vacuum performance, display surface optics and material considerations. The focus of this paper is to highlight steps taken in attempting to understand which characteristics are of particular significance as applied to the emerging OLED display technology, in addition to brief market considerations of when, and if, OLED could be the right solution for display use in crewed space flight missions.

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display devices; thermal vacuum; radiation; light emitting diodes; spacecraft environments	26	

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Unclassified	Unclassified	Unclassified	Unlimited