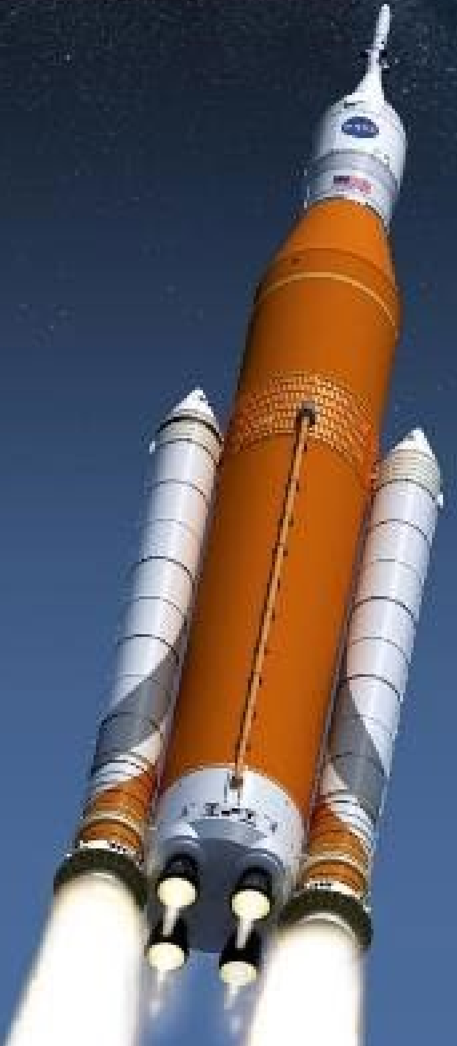


Spacecraft Lighting Systems
Challenges & Potential for Innovation

NASA & Supporting Contractor Discussion Panel

Toni Clark, P.E, Ricco Aceves, Michael Rollins, Ryan Amick

Spacecraft Lighting Systems Panelists

- Toni Clark, P.E.: Human Health & Performance Contract Fellow for Spacecraft Lighting Environments (Leidos)
- Ricco Aceves: Project Engineer for the xEMU Spacesuit primary lighting system (NASA)
- Michael Rollins, PhD: Spacecraft Photogrammetry Expert (Jacobs)
- Ryan Amick, PhD: Human factors expert on spacecraft environments (KBR)

Exploration habitats will have a completely different orbital lighting environment than compared to the ISS. The change in environment impacts external and internal con-ops for performance metrics tied to the visible lighting environment.

How should this impact our use of real or simulated light for crew members and imaging systems?

What innovations are we not using today that could be game changers for exploration spacecraft?

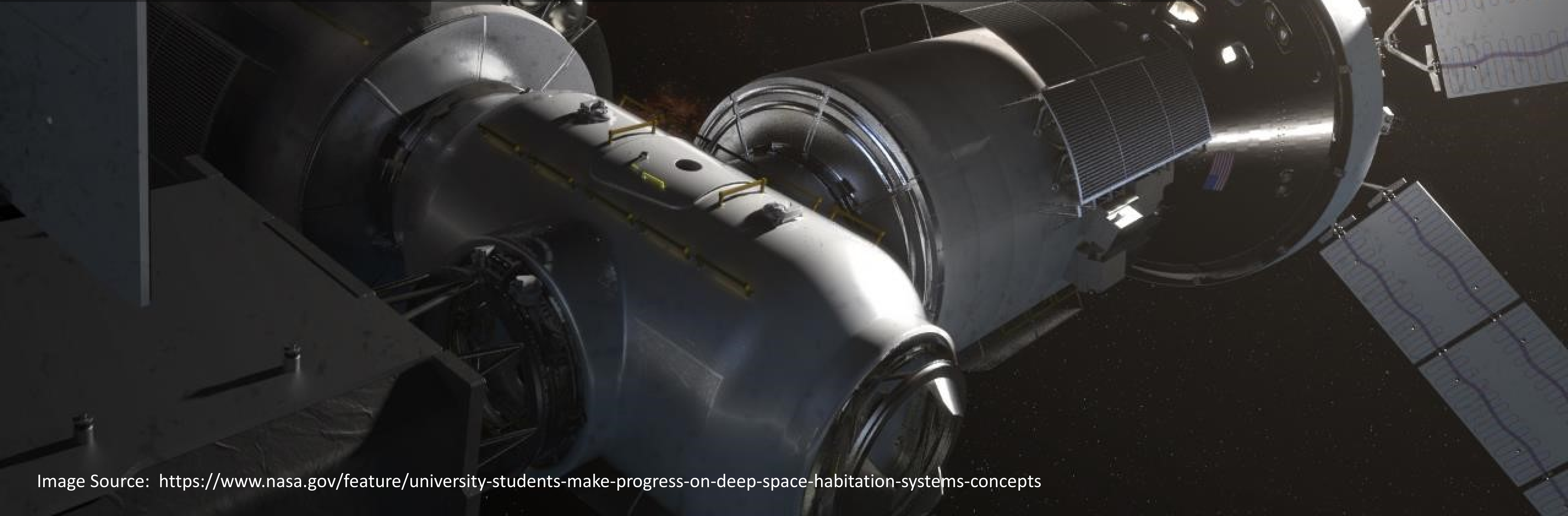


Image Source: https://www.nasa.gov/feature/university-students-make-progress-on-deep-space-habitation-systems-concepts

Why Does the Spacecraft Environment NEED Great Lighting Innovations

Spacecraft operations both inside and outside the vehicle require innovations to maximize crew and spacecraft systems performance.

Innovation is not just limited to the lamps we use, but also includes:

- System integration of lamps to maximize potential performance of the illuminated environment
- Controls systems innovation to automate light sources
- Usage of physics based optical modeling software to predict the lighting environment and lamp performance without hardware testing

The following series of NASA images from ISS captures the heart of opportunity when it comes to lighting systems design.

A Cluttered Workspace Where EVERY Surface Matters….

Image Credit: NASA

There are many opportunities to improve workspaces like this, including optimization of light source placement and automation of lamps to reduce power usage while optimizing crew time.

Image Credit: NASA

A Beautiful Workspace With Challenging Inspection Requirements

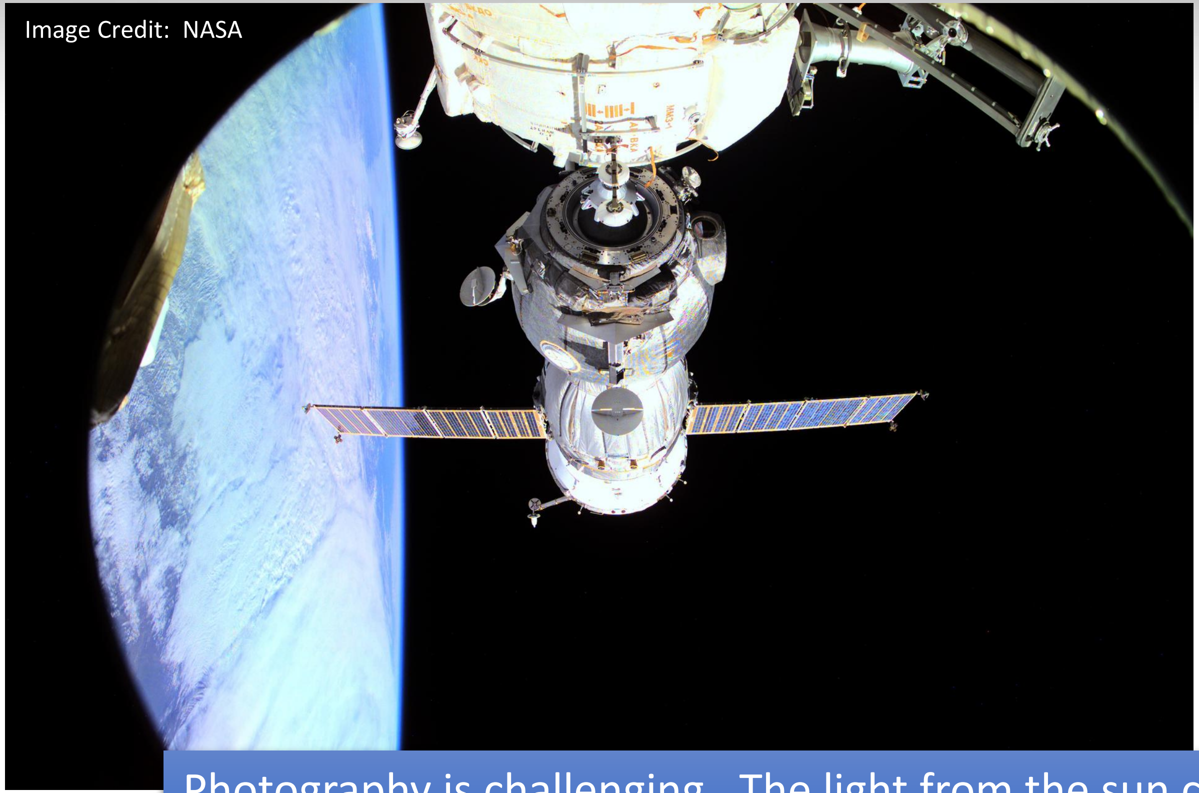


Image Credit: NASA

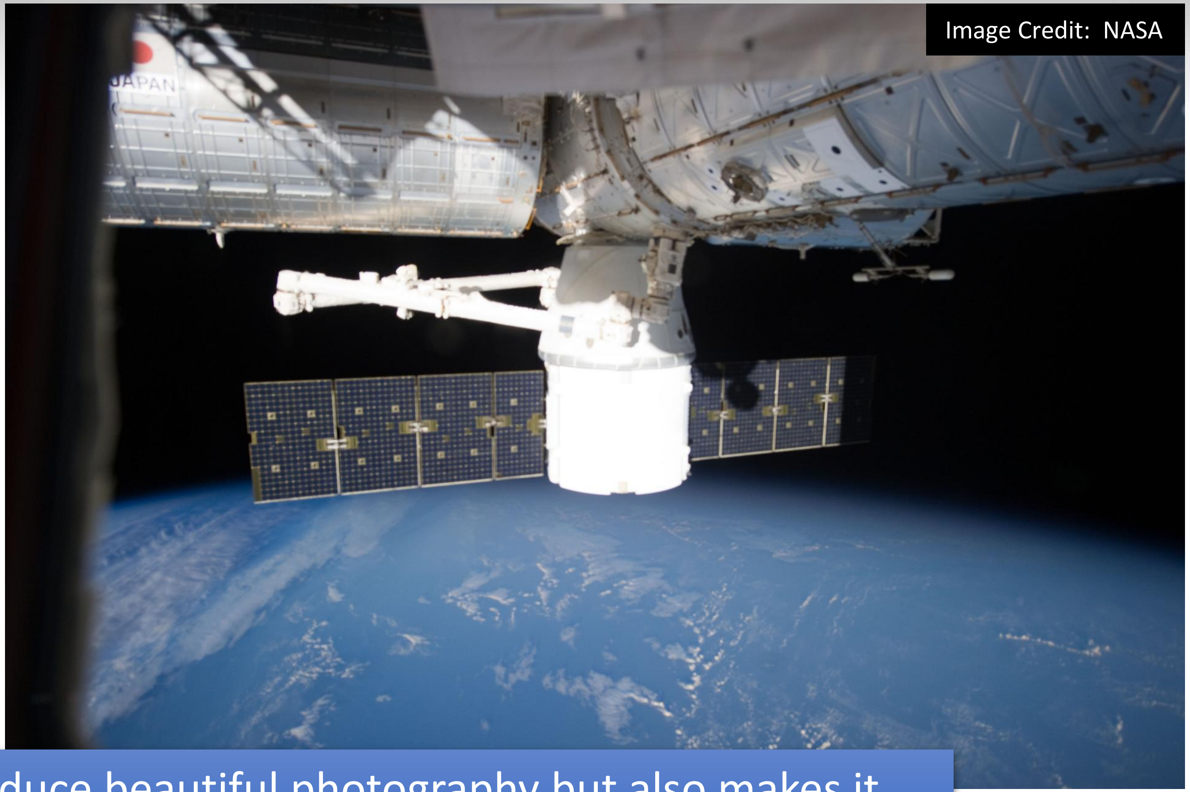


Image Credit: NASA

Photography is challenging. The light from the sun can produce beautiful photography but also makes it difficult to avoid pixel saturation in part of the image most critical for inspection. Light sources mounted on the exterior of the spacecraft can be used offset imagery problems due to glare.

A Harsh Workspace That Changes Every 90 Minutes


Image Credit: NASA


Image Credit: NASA

These images were taken by the same camera but at different times during the ISS orbit. What if an important task needs to continue through eclipse? What if the darkness is perpetual? Good supplemental lighting is not trivial.

A Workspace Where Mistakes In Judgement Could Be Catastrophic

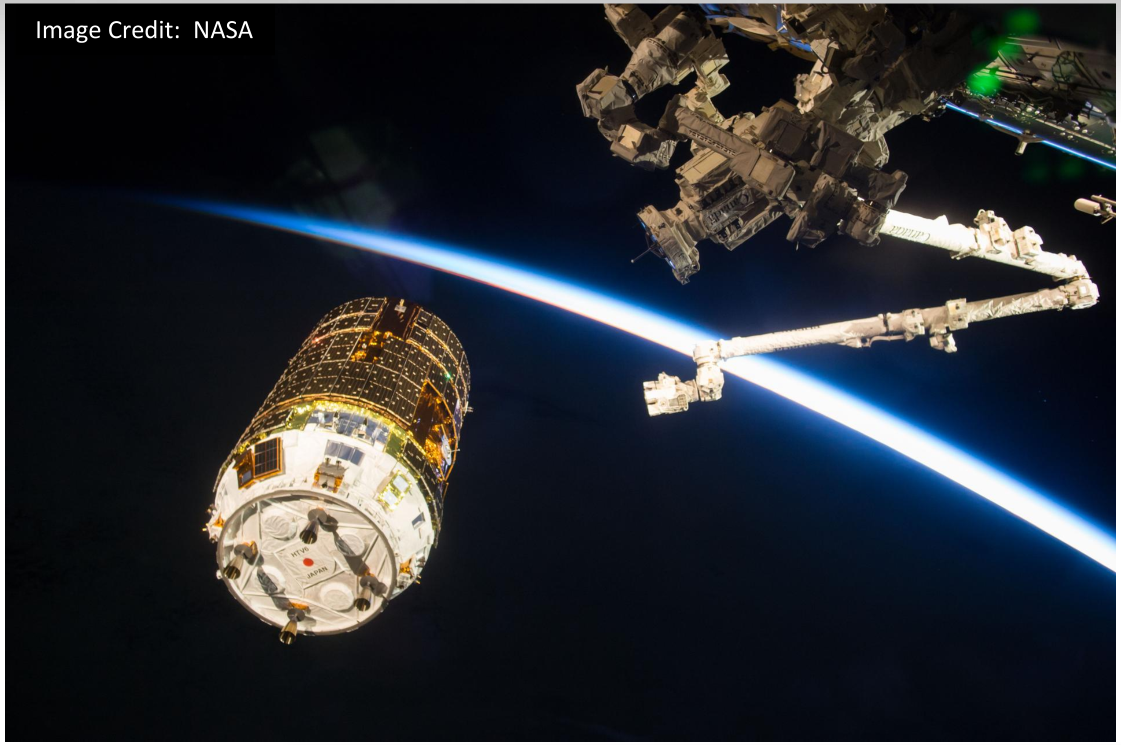


Image Credit: NASA


Image Credit: NASA

Judgement of surface details and the geometry of objects large and small is important for time sensitive and inspection critical tasks. Good light source and camera placement enables remote operations without the need of an EVA inspection.

Critical Tasks With Only A Few Flashlights to See By

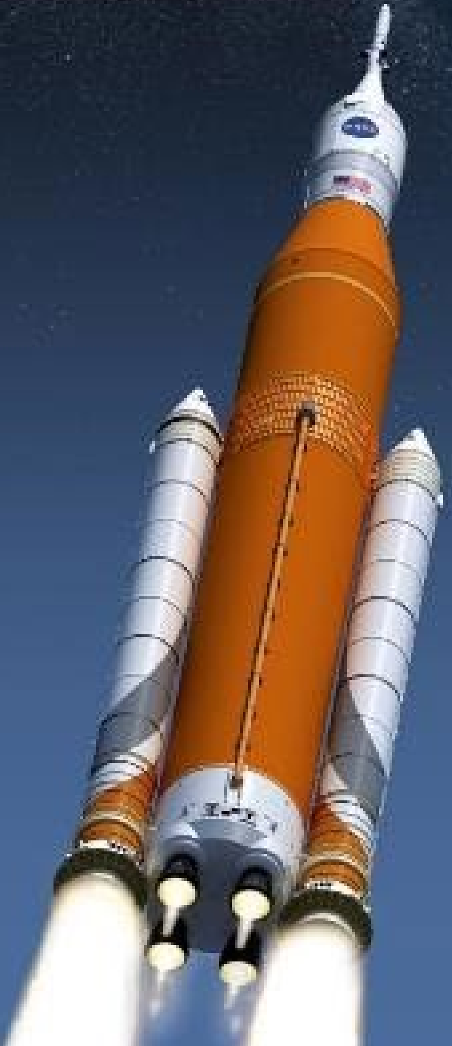
This photo shows an Extravehicular Activity (EVA) when the sun was in eclipse. The crew member only has the lights on their suit to perform their important maintenance task.

Imagine situations where you have been outside during nighttime, where there was minimal to no lights from buildings, and you needed to either get to safety or had to repair equipment on your car, with only a flashlight.

In those situations, would you have wanted a better flashlight, or more flashlights?

This photo was taken the day a supporting crewmember needed to make an emergency return to the airlock due to water in their helmet.

Image Credit: NASA



Johnson Space Center Lighting Lab Capabilities

Toni Clark, P.E. Human Health & Performance Contract Fellow for Spacecraft Lighting Environments (Leidos)

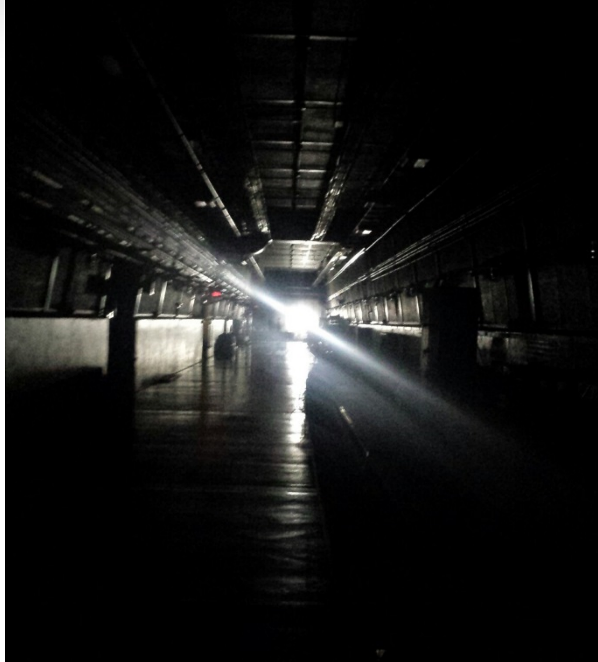
Johnson Space Center Lighting Lab Capabilities

Capability	Application	Associated Equipment
Simulate direct and indirect lighting at orbital light levels.	Development and validation of spacecraft lighting and camera performance requirements	Orbital Light Source Simulator, Suite of Light Measurement Sensors
Provide ISS lighting in controlled facility.	Validate hardware interface with ISS lighting.	ISS SSLA EDU, Controlled White and Dark Room
Maintain inputs into computer lighting models to validate lighting scenarios.	Verify impact of lighting changes; validate lighting for tasks, berthing, photography/video. Maintain updated database for ISS model.	Imaging Goniophotometer; Hemispherical Spectral Reflectance Meter; High Resolution Spectral Irradiance & Radiance Meters
Develop programmable lighting systems.	Support Circadian rhythm and environment-human studies. Promote smart luminaire operation using automation.	DMX512 Lamp Hardware and Software Operation

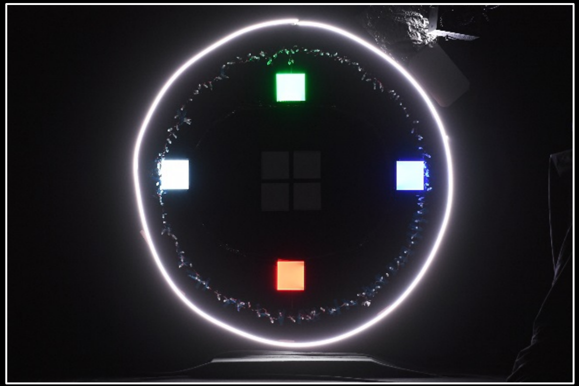
Lab Tests of Lighting Systems

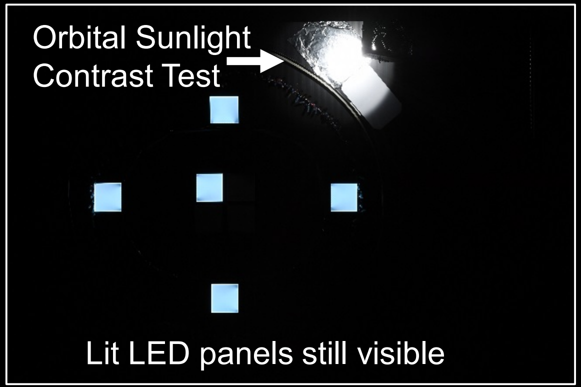
Calibration of Camera/Lighting Systems

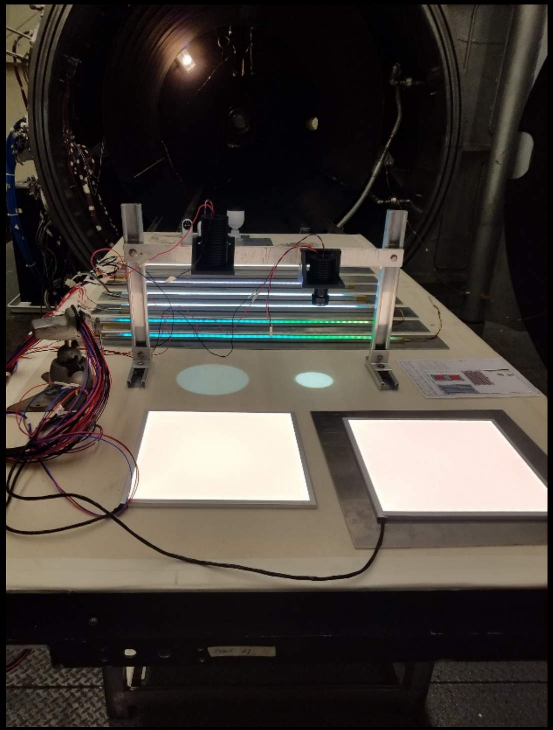
The orbital lighting environment creates harsh shadows and glare. The lighting lab provides orbital lighting environments to assist in the test of cameras and external lighting concepts.



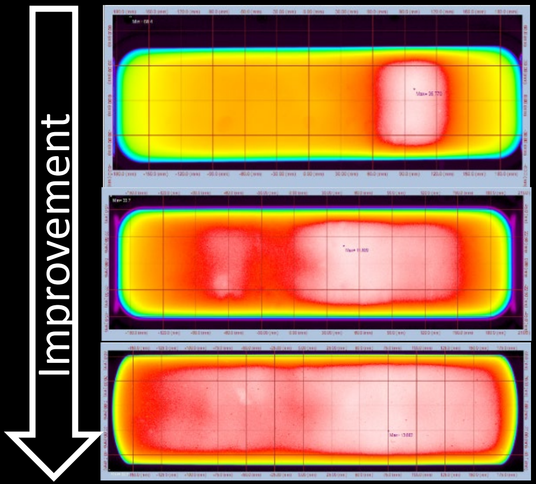
Illuminating target at 130,000 lux.
Light seen here is a reflection.







Certification testing of commercial light sources in a vacuum chamber for usage at 4.2PSI



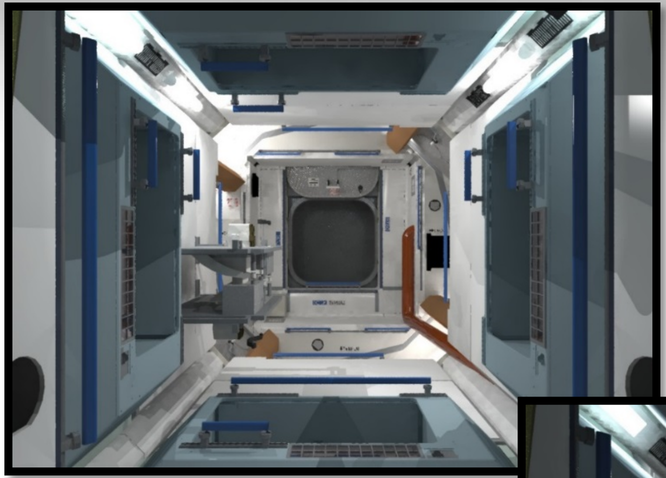
Demonstration on how imaging colorimeter was used to improve the uniformity of luminance for a light source

Recent Lighting Lab Support Work

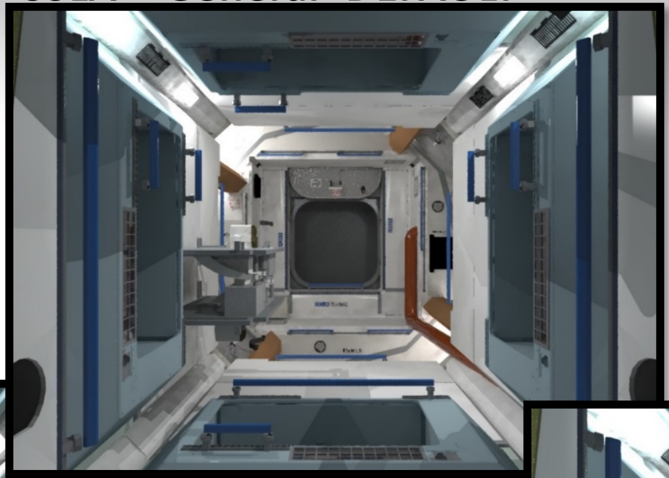
- Development of a NEW lighting system for EVAs to be installed on the xEMU, benefiting ISS, Gateway, Lunar programs.
- Computer simulation of a lighting solution for team developing a method to irradiate a water tank with ultra violet light to help maintain a clean water source, benefitting ISS.
- Assistance in the development of lighting requirements for NASA's new Artemis program
- Lighting lab testing and computer lighting simulation support of the Orion lighting system.
- Development of a lighting system to outfit Johnson Space Center's 20 Foot Vacuum Chamber that meets environmental hazards of the chamber while demonstrating new lighting technologies.
- Collaboration with JSC's Microbiology lab to investigate the usability of violet light as a microbial countermeasure.

Modeling of Interior Lighting Environments

Fluorescent

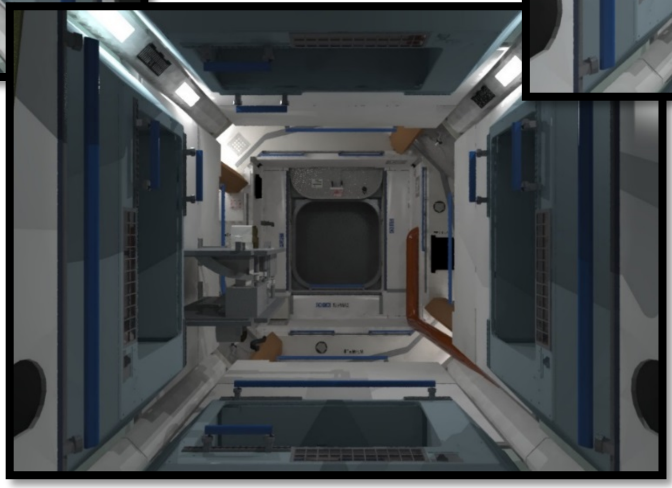


SSLA – General -DEFAULT

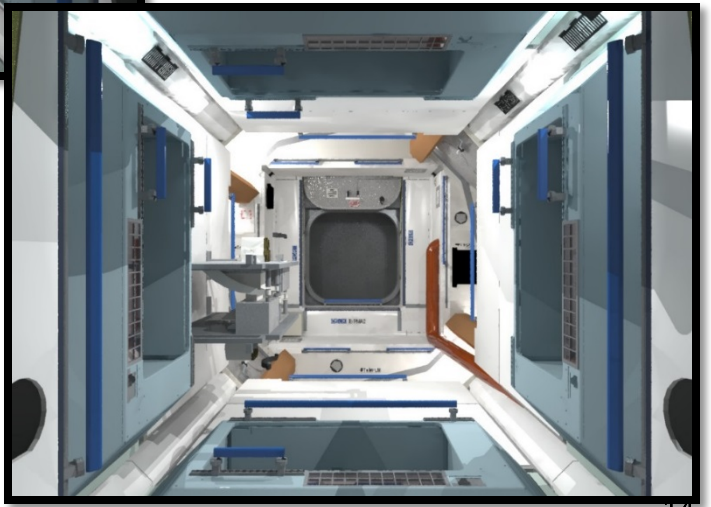


ISS Node 2 perceived light intensity images were developed using Radiance lighting analysis software.

SSLA – PreSleep - DEFAULT



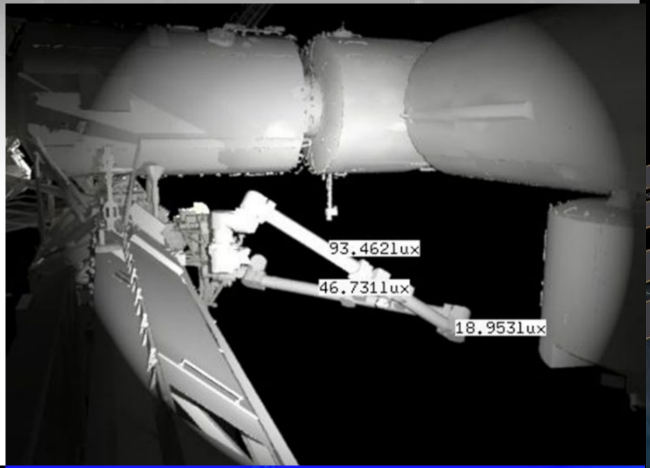
SSLA – PhaseShift - DEFAULT

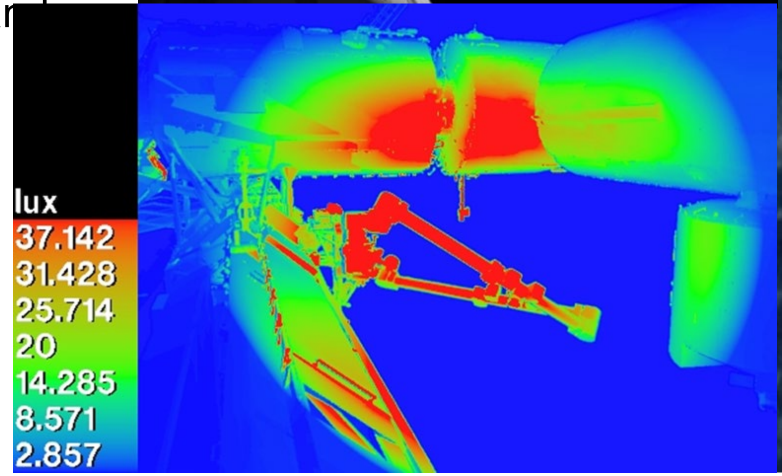


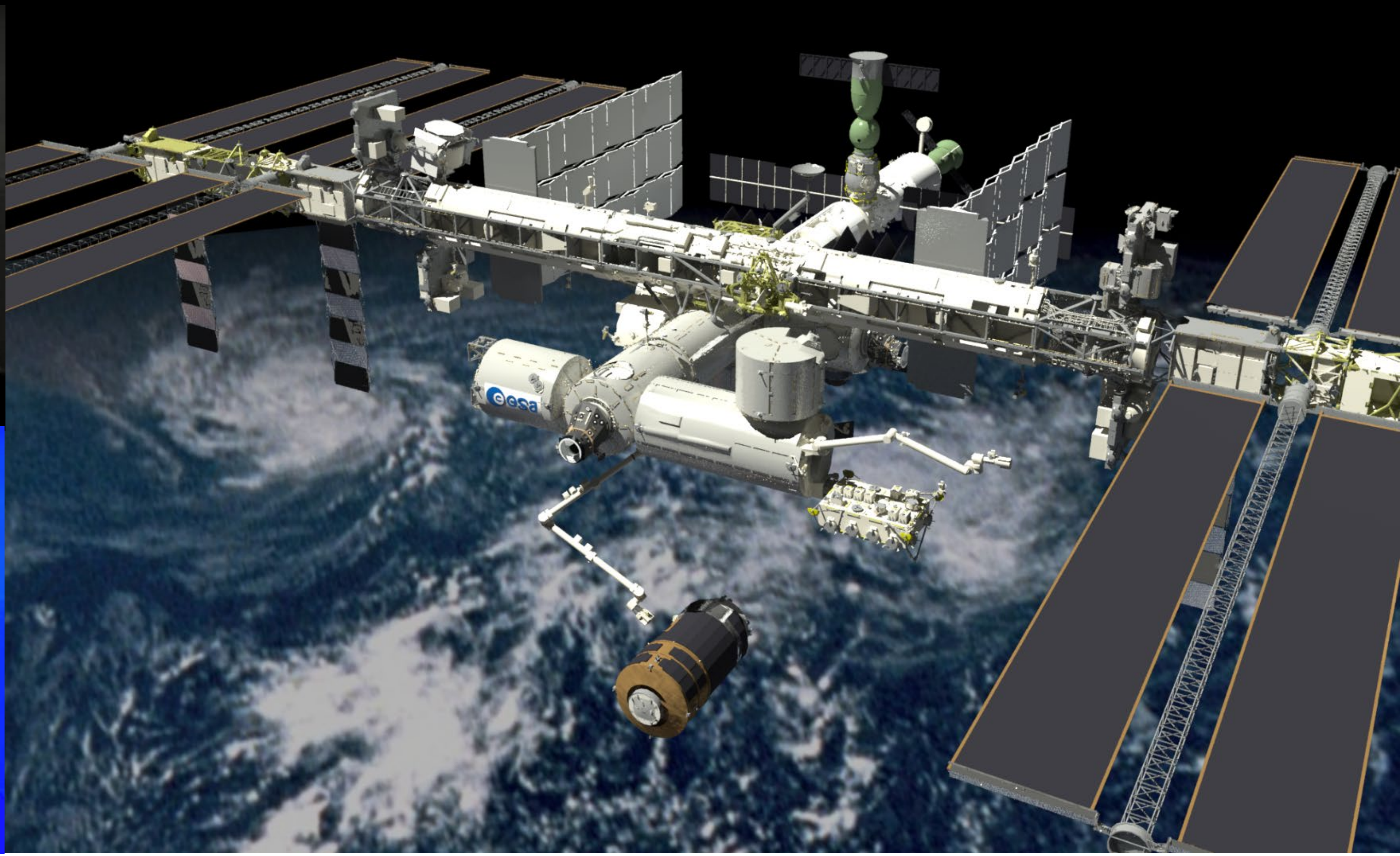
Modeling of External Lighting Environments

Images developed using Radiance lighting analysis software.

Visualizations are used to show astronauts and mission planners how the environment may look and what to expect for light level specific tasks.

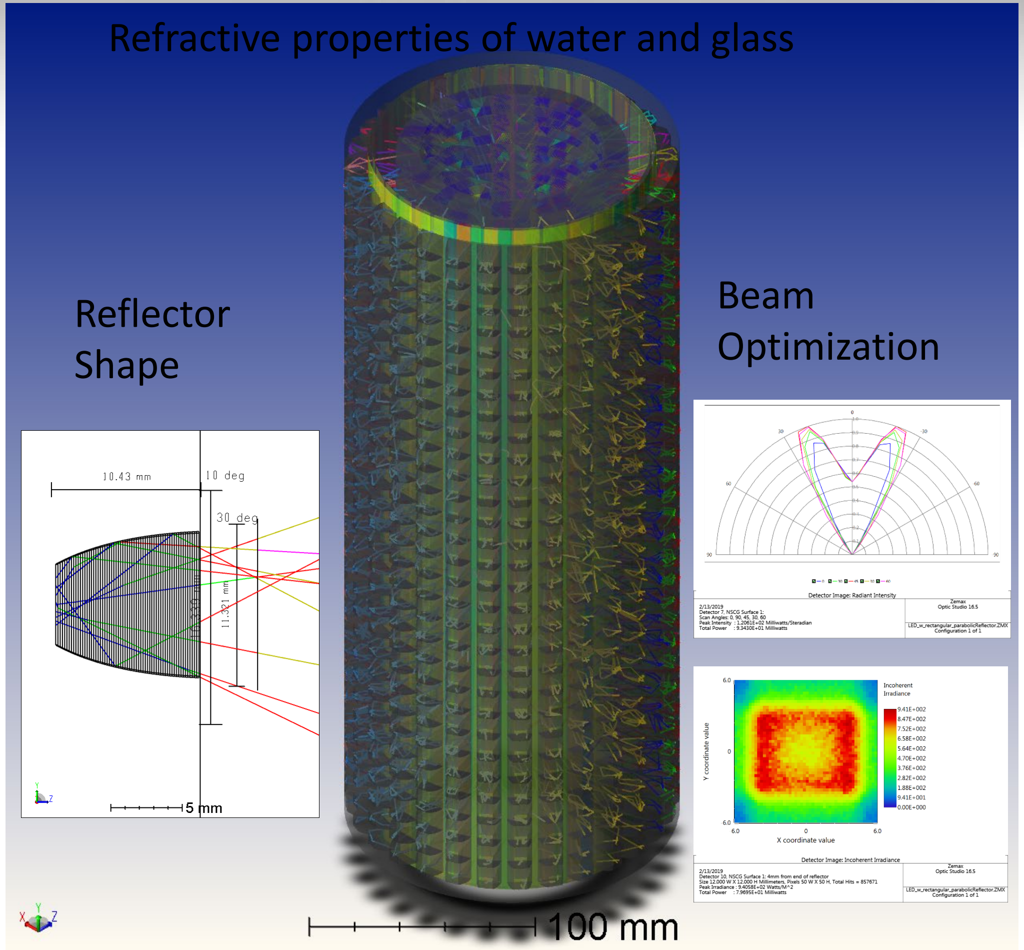




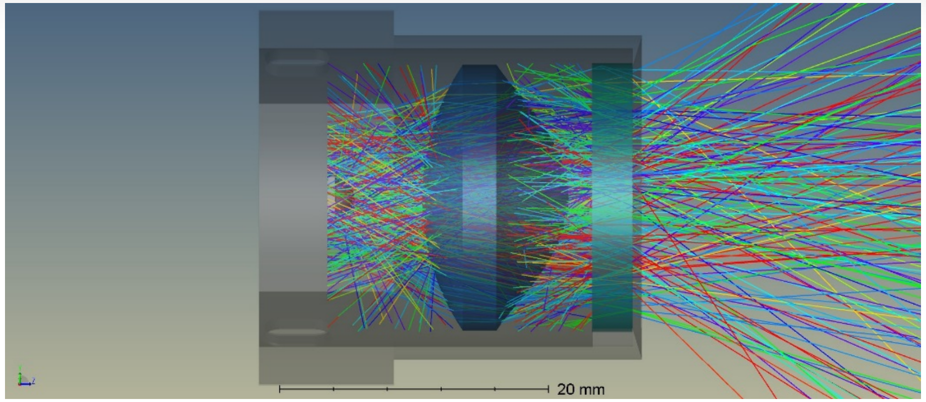


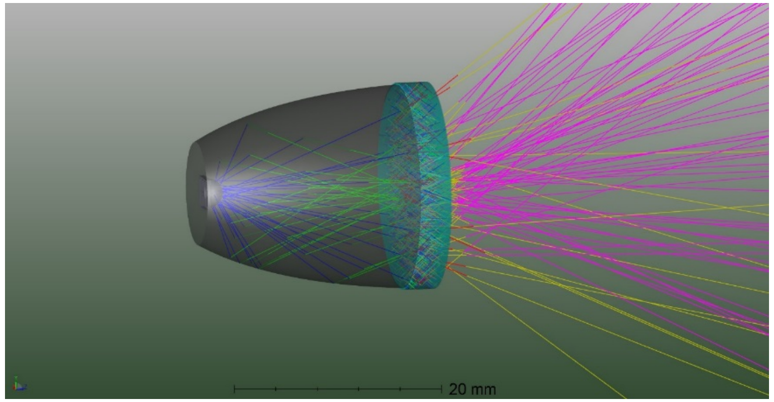
Custom Optical Light Source Development

UV Water Tank Optical Design

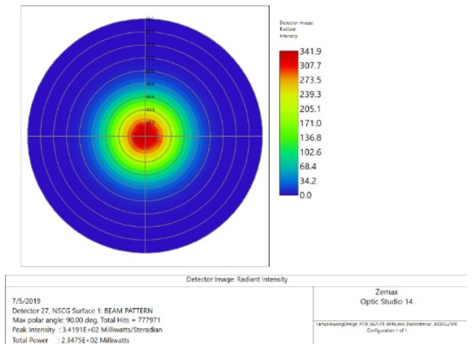


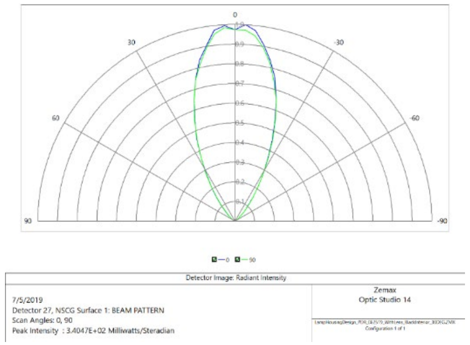
xEMU Headlamp Design





Custom Lamp Beam Pattern Predictions

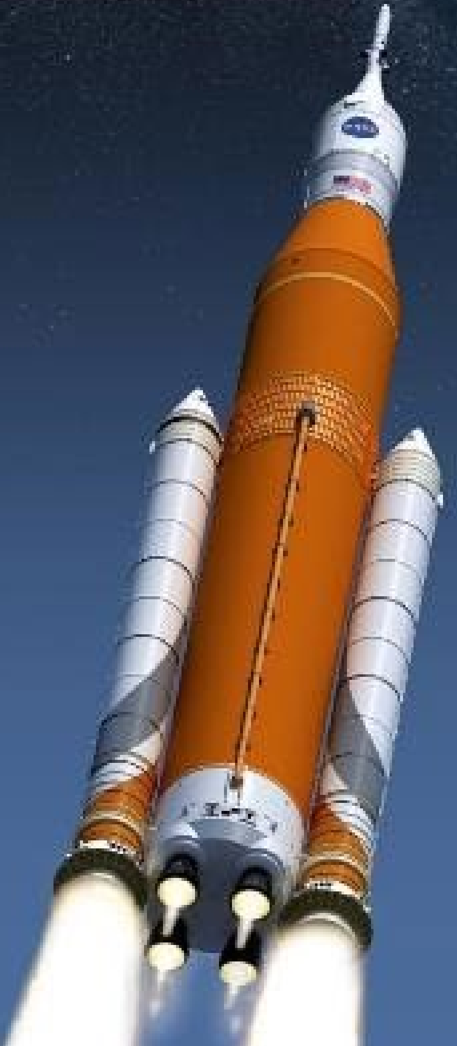




Requirements verification & development

The Lighting Lab is used to both develop requirements verifications and verify project requirements.

Requirement	Project
NASA STD 3001: Chromaticity, Color Fidelity, Sleep	Update to NASA STD 3001, requirements for light source chromaticity, color fidelity, and spectrum.
SSP 50005 E: Illumination Levels, Reflected Glare, Emergency Lighting	Evaluate ISS operational compliance to required general and task light levels. Evaluate light from reflected glare from new payloads. Verify performance of photoluminescent decals for emergency indication.
CTSD-ADV-1188B & EVA-EXP-0032	xEMU SRR Requirements Review
End Item Lamp Specifications	ISS Solid State Lighting Assembly (SSLA) Specification, Orion's interior lamp specification, xEMU spacesuit primary lighting system specification.
SSP 50808: Illumination Levels, Emergency Egress, Spacecraft Viewing	Visiting Vehicles (Commercial Crew) Interior Light Level Compliance, Emergency Egress of Visiting Vehicles, and Verification approaching spacecraft meet ISS luminance requirements.
SSP 50808, Emergency Egress	Visiting Vehicles Emergency Egress



Exploration EMU (xEMU) Lighting System

Ricco Aceves

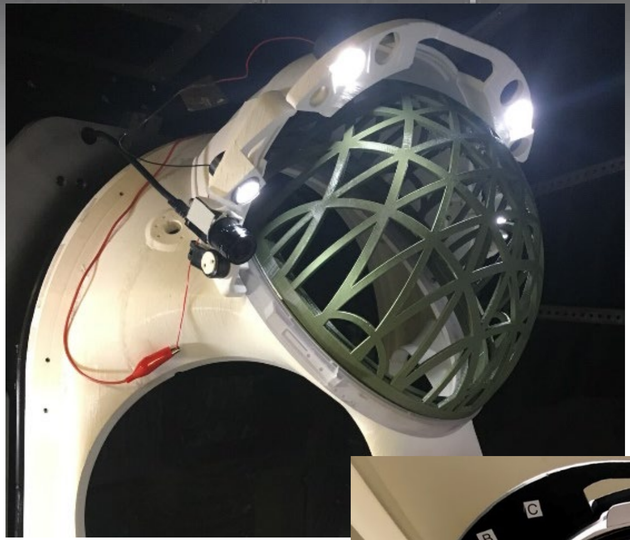
Informatics Lighting Lead (NASA)

Initial Lighting Development

- Utilized EMU lights to maximize reuse of EMU hardware
  - Save development cost and time
  - “If it isn’t broke, don’t fix it”
- Iterative fit checks and analysis determined the EMU lights would not meet lighting requirements
  - Pointing capability limited by helmet structure
  - Light shines into helmet glass, creating glare
  - Spot lights are too narrow (20 degree beam)
  - Power consumption is greater than we’re allocated
- Driven to develop new lighting system for xEMU

Iterative Prototyping and Testing

- Lighting architecture iterative testing
  - Explored multiple lighting options since February
  - Built makeshift dark room for engineering evaluations
  - Refined list of feasible locations
  - Refined lighting requirements – illumination levels, lighted area, human factors, controls, etc.
- Results
  - Lights will be divided into Work and Translational lights
  - Lights will be mounted to side of helmet

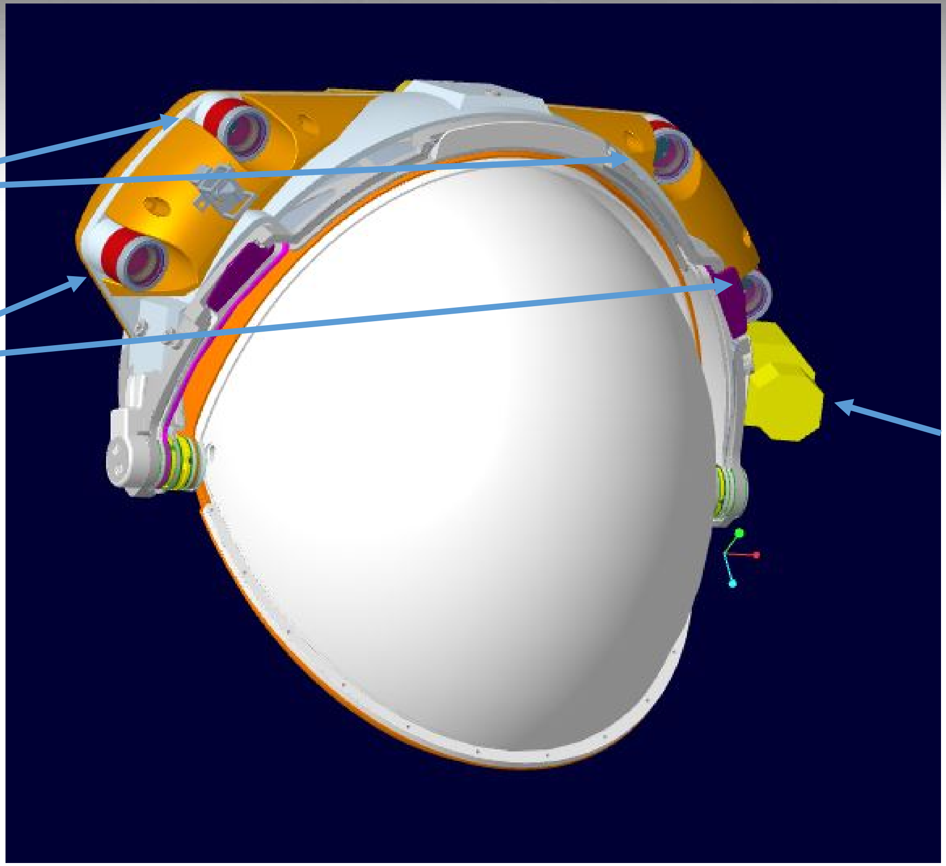


New Lighting System

xINFO Lights

Translational Lights: Focused towards the surrounding environment (50x18 degree elliptical beam)

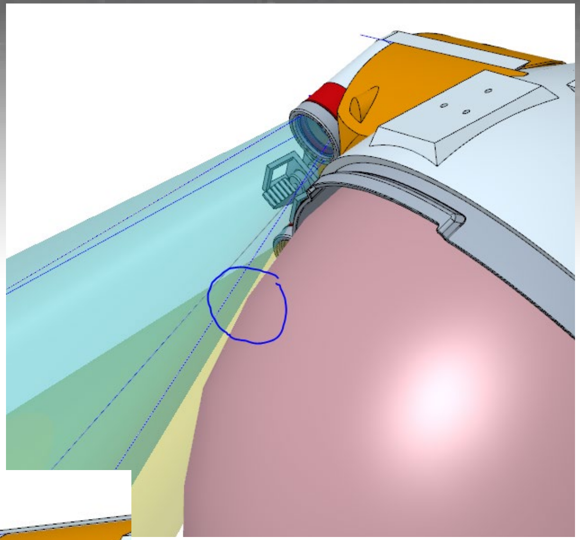
Work Lights: Focused towards the 2-handed work envelope (25 degree circular beam)

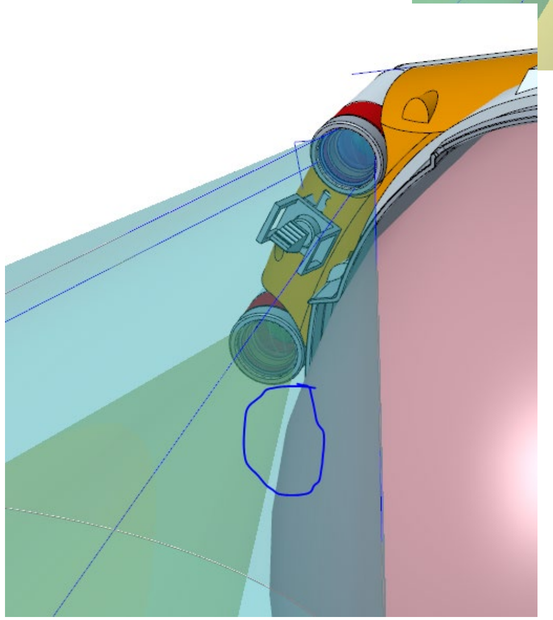


xINFO Camera

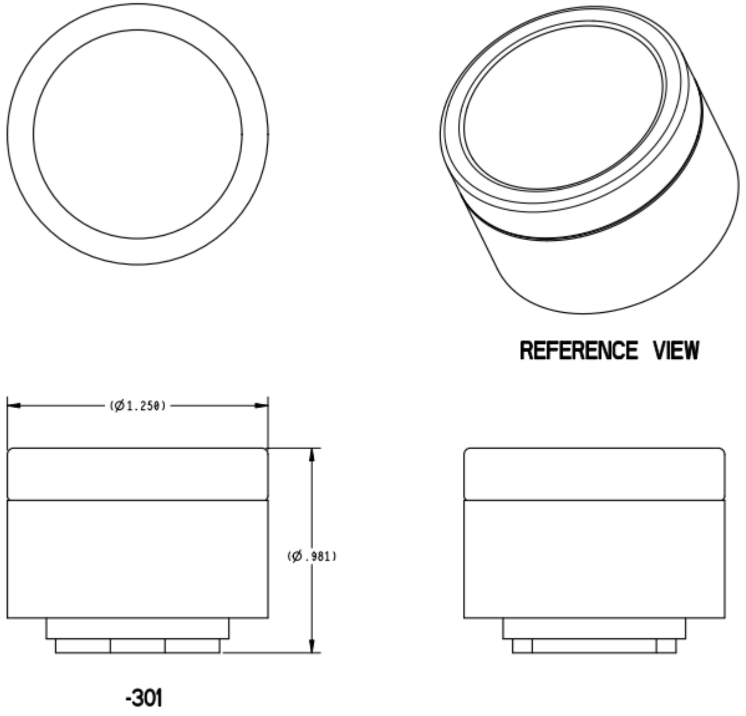
Design Challenges

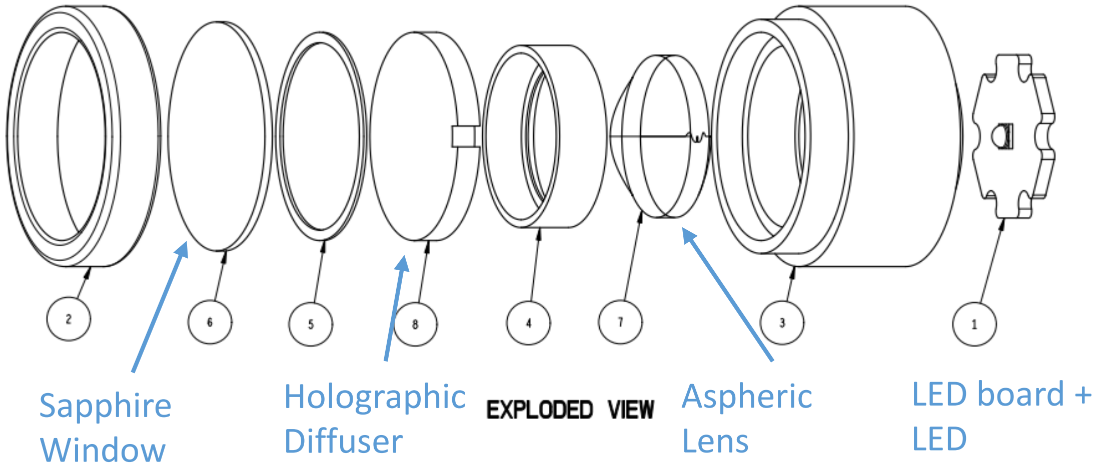
- Hiding LED and preventing glare
  - Potential to blind partnering Extravehicular Activity (EVA) crewmember
  - Suit helmet bubble contains elliptical geometry making it difficult to prevent light from making contact
- Keeping system under 6W while providing adequate lighting
- Dissipating heat from lamps and electronics
- Preventing light loss internal of lamps





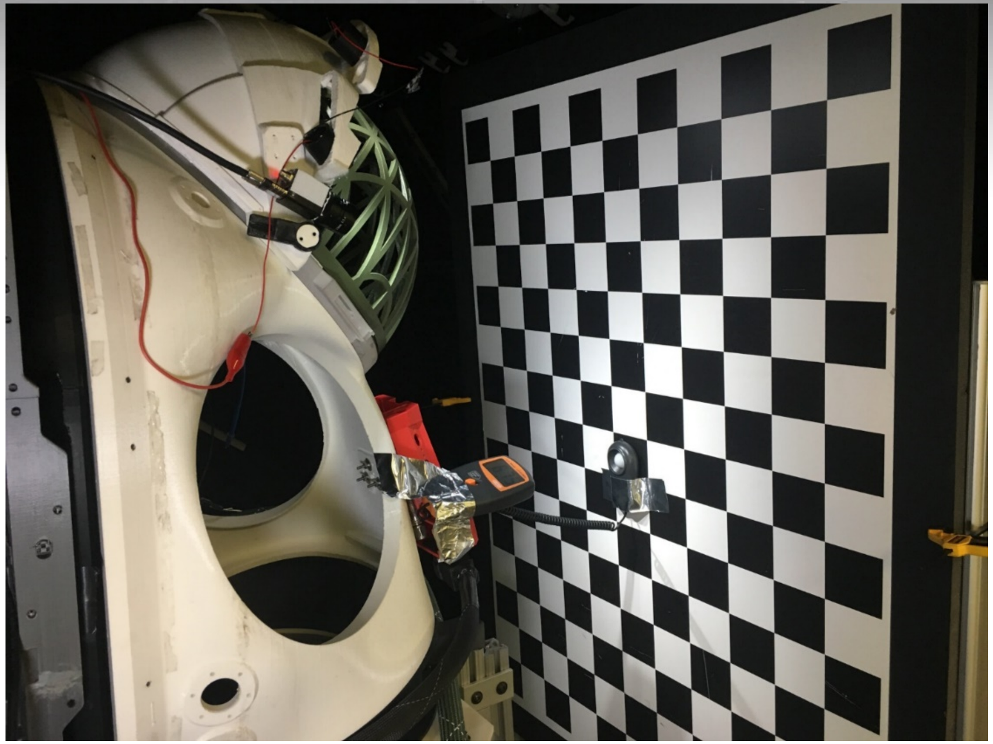
Inside the Lamps





QTY	CAGE CODE	PART NUMBER	DESCRIPTION	MATERIAL	SPECIFICATION	FRAC CRIT	TRACE CODE	REF DES	ITEM	FL NOT
1	97197	54500	DIFFUSER, 30°, 25 MM DIA.			N	TE		8	
1	97197	35052	ASPHERIC LENS			N	TE		7	
1	97197	39-230	SAPPHIRE WINDOW, UNCOATED 25.4 MM DIA. X 1 MM THK			N	TE		6	
1	21356	SDN1310XXXX-001	SPACER, SAPPHIRE WINDOW			N	TE		5	
1	21356	SDN1310XXXX-001	RETAINER, LENS			N	TE		4	
1	21356	SDN1310XXXX-001	LIGHTING SHELL, XINFO BAND			N	TE		3	
1	21356	SDN1310XXXX-001	COVER, SAPPHIRE WINDOW			N	TE		2	
1	21356	SEN13103631-301	LIGHTING CAPSULE LED, ASSEMBLY			N	TE		1	
	21356	-301	LIGHTING CAPSULE ASSEMBLY			N	TE			

Illumination Comparison

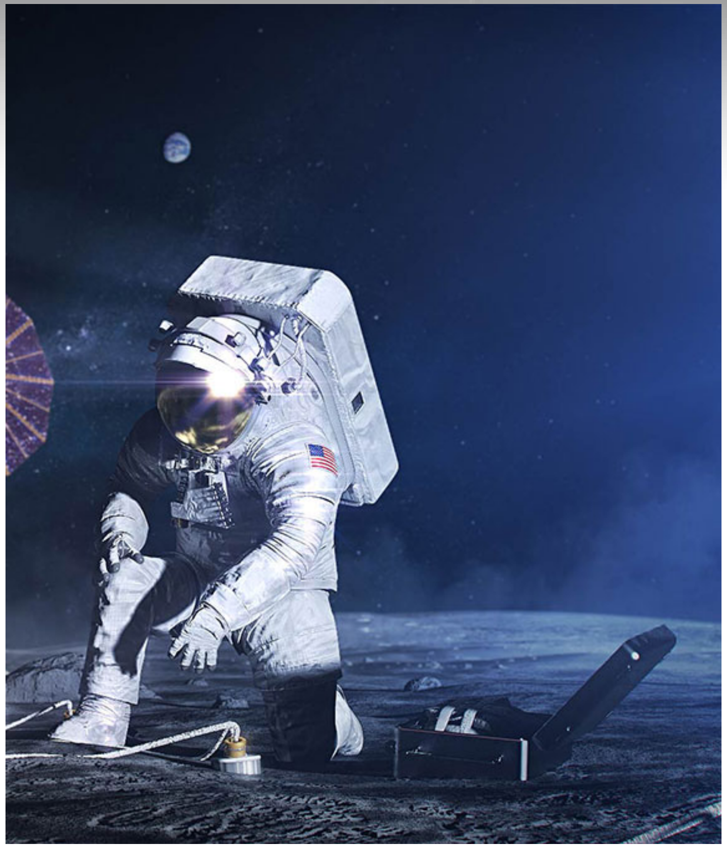


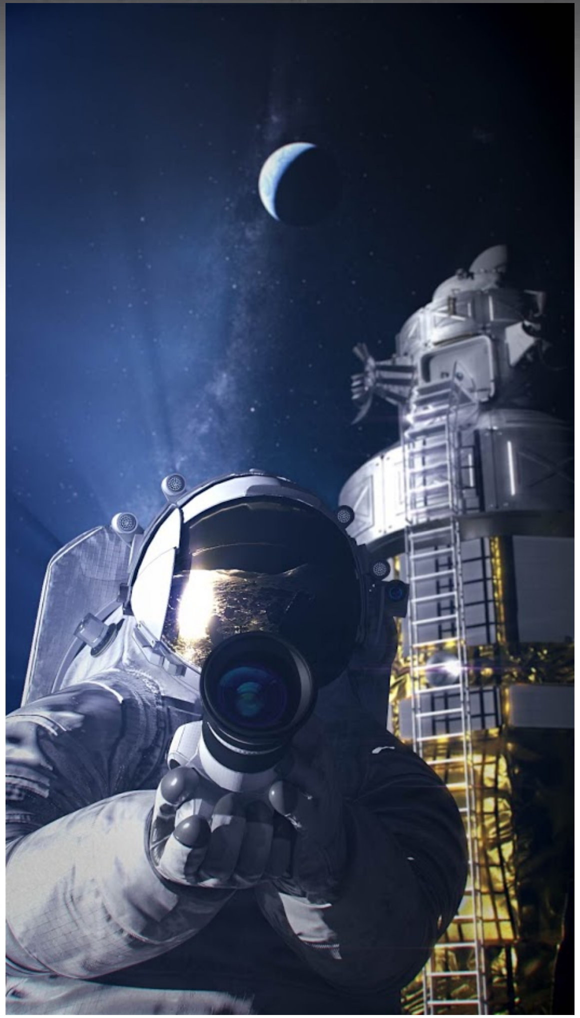
Uniform Distribution

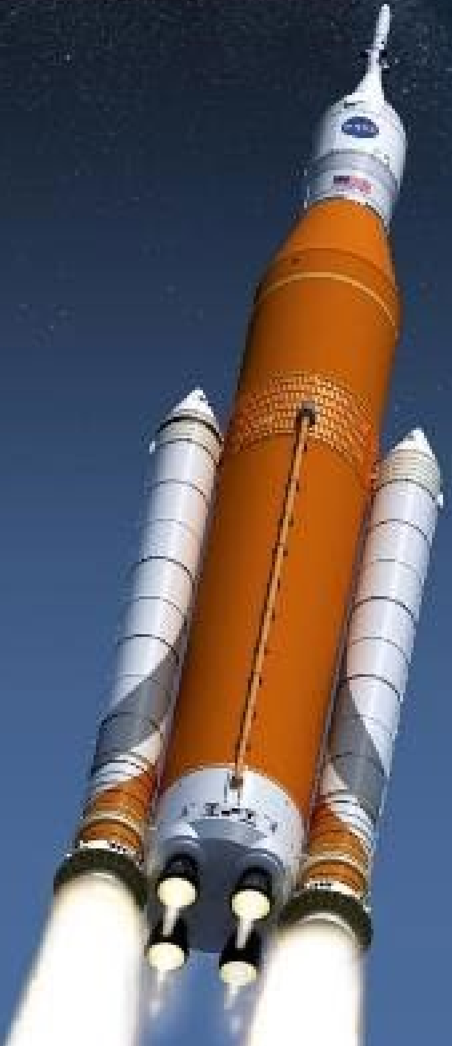
Hard illumination
(current ISS EMU solution)

What's next?

- Develop concept of operations and requirements for Gateway, Human Lander System (HLS) and Lunar programs
- Develop adequate lighting system for deep space application
  - External vehicle lighting
  - Rover lighting
  - Lunar flashlights
  - Upgraded suit lighting







Why Lighting Is Important for Spacecraft Imagery

Michael Rollins, PhD, Spacecraft Photogrammetry Expert (Jacobs)

Toni Clark, P.E., Human Health & Performance Contract Fellow for Spacecraft Lighting Environments (Leidos)

Camera Design and Imagery Operations Rely on Understanding the Lighting Environment

Cameras and imagery have a critical role in NASA operations.

- Cameras provide a safe alternative where direct crew observation is too hazardous or impossible due to habitat or spacecraft geometry.
- Cameras can be used in exploratory and autonomous operations leading up to human exploration of a worksite.
- Cameras provide real time feedback on the geometry of an active worksite for activities like robotic servicing and spacecraft docking maneuvers.
- Cameras can be used for inspection for damage of spacecraft surfaces from micrometeorites and verification of successful deployment of critical equipment like solar panels.
- Cameras can be used to support quantitative spacecraft structural deployment and separation event performance analysis.

Camera & Imagery Operations Require Planning

Worksite Surveys

- Geometry of worksite and how natural lighting illuminates critical surfaces
- Location of artificial light sources and how they could enhance the lighting environment.
- Location of cameras and where to make the most impact despite the limitation of the environment.
- Mission Timeline and how changes in the natural environment due to vehicle location impacts planning of imagery operations

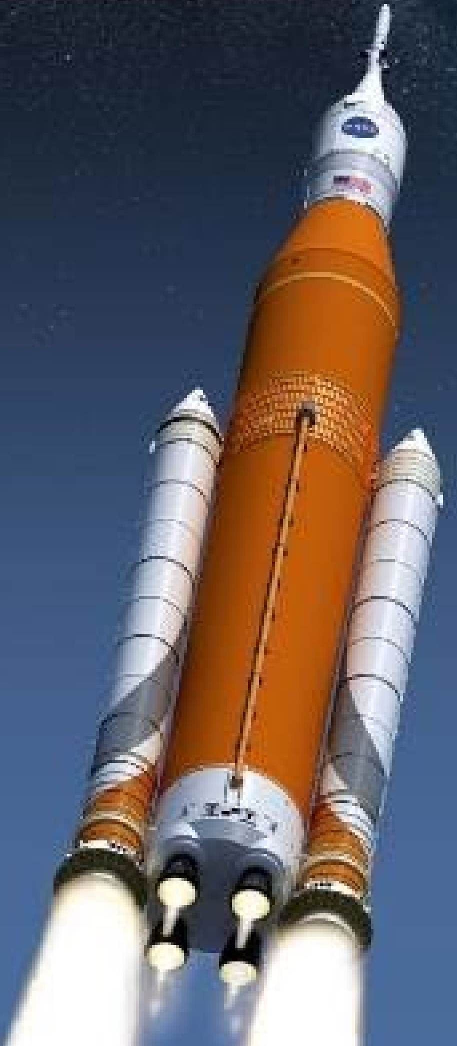
Methods

- Computer based lighting analysis
- Architectural line of sight evaluations
- Camera parameter surveys to find best equipment for expected environment.
- Knowledge of, and often, control of lighting is crucial to choosing proper camera settings for successful imaging.

Camera & Imagery Operations Require Testing

Physical Testing of Cameras In Relevant Environments

- Worksite surveys yield information important for physical verification of an integrated camera and lighting system.
- Cameras are tested in a relevant, simulated, or actual environment to verify camera parameter settings and issues with the integrated environment.
  - Camera performance issues: Flicker, Glare, Exposure, Aperture, Field of View, Location
  - Lighting Environment: Orbital Lighting or Interior Lighting. Light spectrum, intensity, distribution, and frequency modulation are important to duplicate.
- Findings are used to refine camera and lighting requirements prior to the operation or before the hardware is built and integrated into the environment



Human Factors in Habitat Lighting

Ryan Z. Amick, PhD

Habitability Discipline Scientist

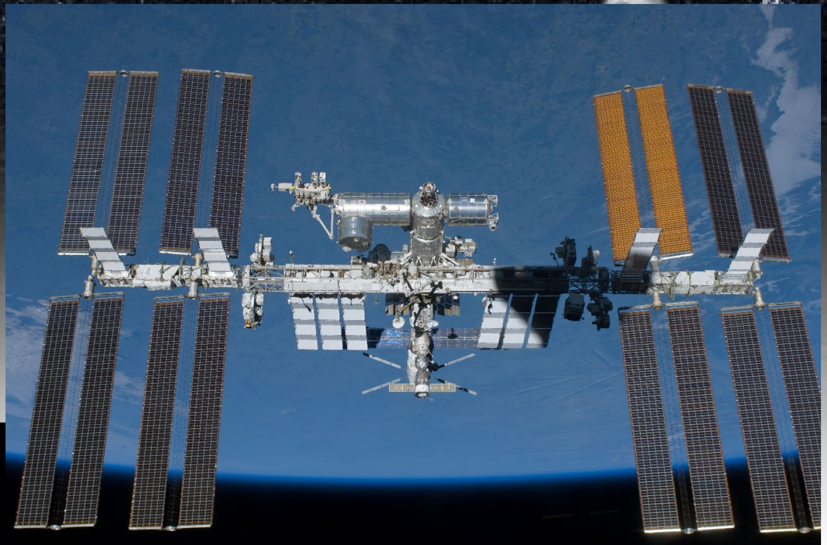
xEMU Informatics Human Factors Lead

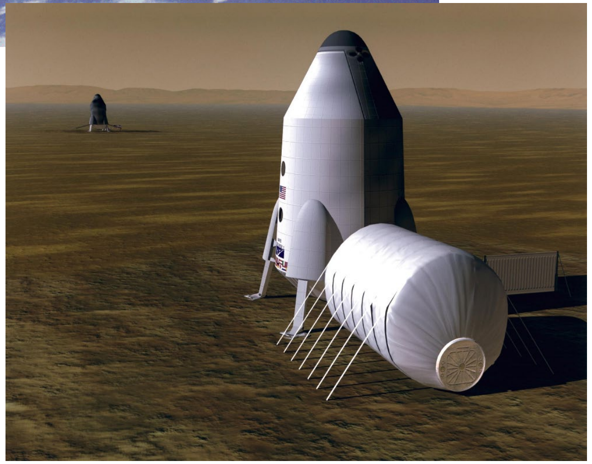
Habitat Design

Environmental Conditions

Human Capabilities

Safe and Efficient Human Performance During Space Missions





Design Factors to Consider

- Anthropometric and Biomechanical Limitations
- **Visual Environments**
- Vibration and g-Forces
- Noise Interference
- Seating, Restraints, and Personal Equipment
- **Visibility/Window Design and Placement**
- Habitat Volume Layout

Design Factors to Consider

- **Visual Environments**
  - Evaluated factors which may contribute to poor visibility both inside and outside of the vehicle/habitat
    - Weather, Haze, Darkness, Dust, Smoke
  - Lighting is critical component
    - Visual perception is primary method of obtaining information about the physical environment
    - Strongest external cue for maintaining circadian rhythms
  - Optimized lighting promotes safety and efficient task performance
- **Visibility/Window Design and Placement**
  - If not optimized can be counter productive to the designed lighting system
  - Concerns include
    - Glare and reflections which create visual obstructions
    - May result in error, injury, poor task performance

Design Factors to Consider

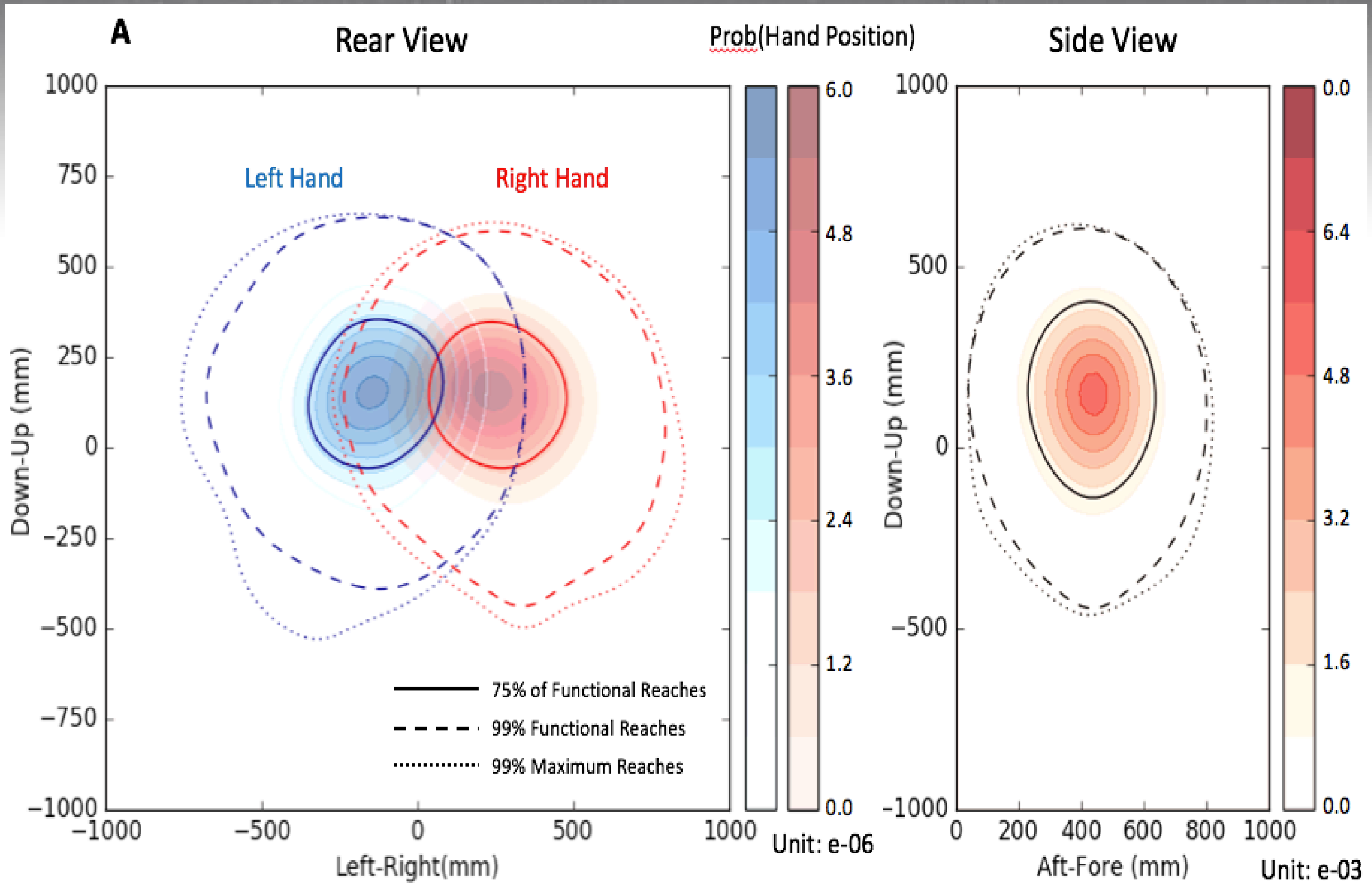
- **Optimizing Visibility and the Visual Environment**
  - Detailed Task Analyses
  - Development of a Concept of Operations
  - Modeling
  - HITL Testing in Ground Based Analog(s)

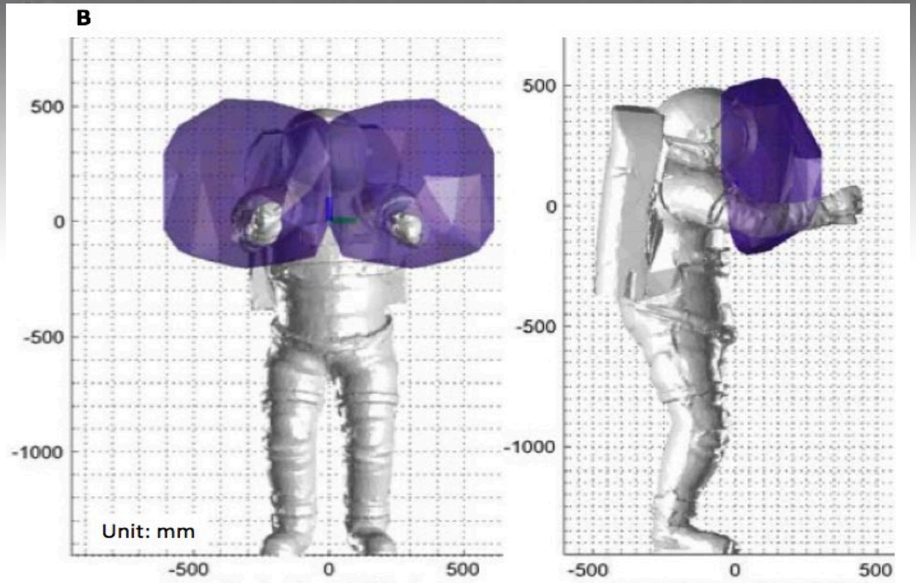
- **Tradeoffs to Consider**
  - Power Constraings
  - Physical Restrictions on Lighting Source
  - Vehicle/Habitat Volume
  - Operator Tasks and Locations

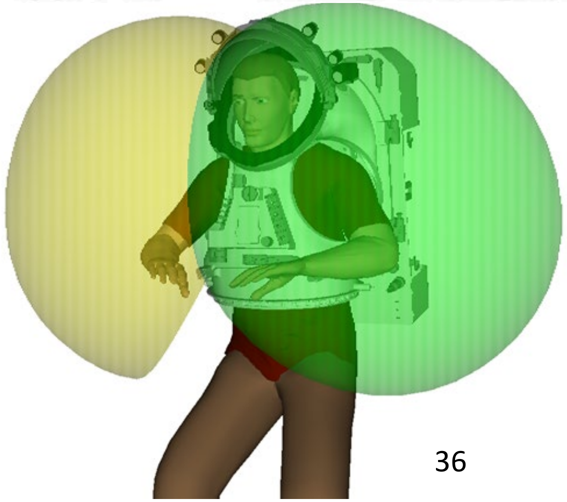
- **Mission Objectives Drive Design Tradeoffs**

Current Work - xEMU Lighting

Current Work - xEMU Lighting

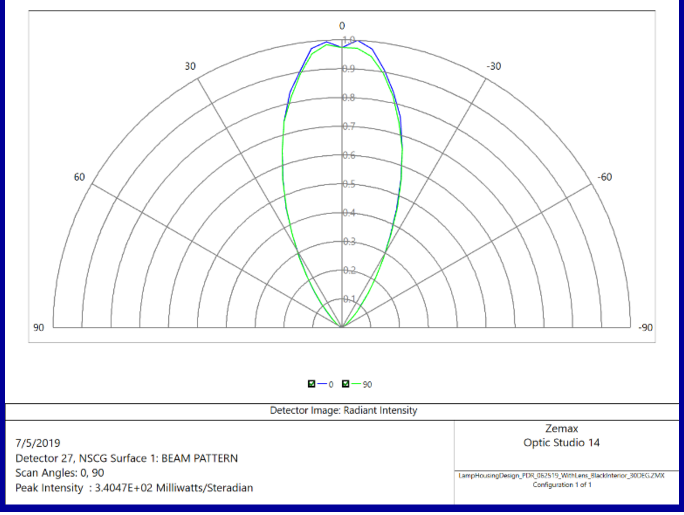


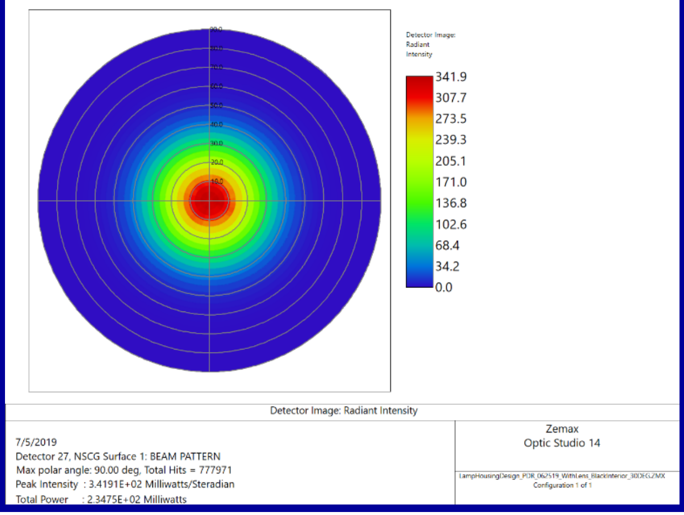




xEMU Lamp/System Beam Patterns

Multiple optical studies were performed to determine an optimal beam pattern shape to minimize entrance of light into bubble while producing good illumination at the target. It was found that 30° Half Angle was the widest tolerance allowed for the beam.



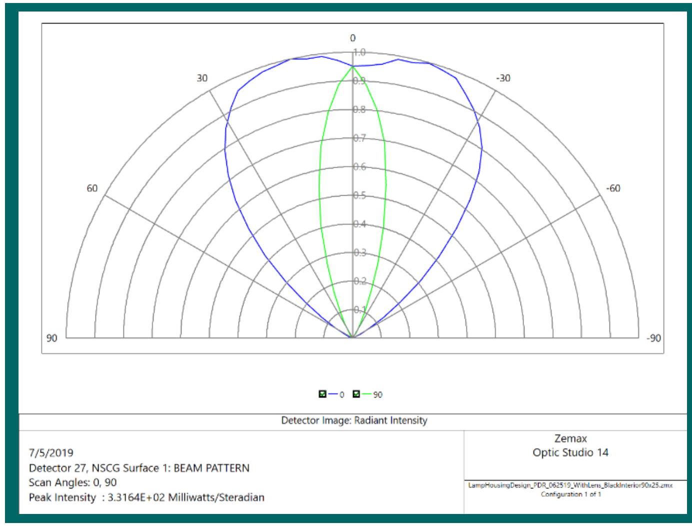


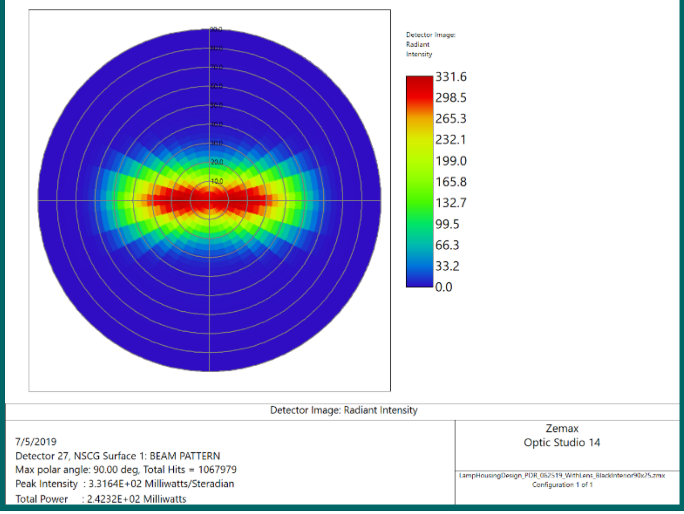
Work Zone Lamp

Beam width ~ 25° Half Angle

This lamp outputs 69.43 lumens

More light is possible if changes are made to housing shape, reflector, and housing color.





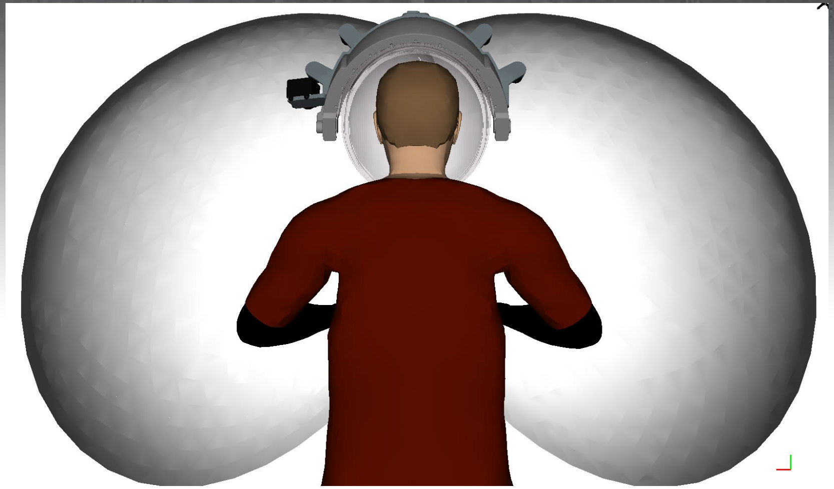
Translational Zone Lamp

Beam shape is 18 ° x 50 ° Half Angle

This lamp outputs 71.67 lumens

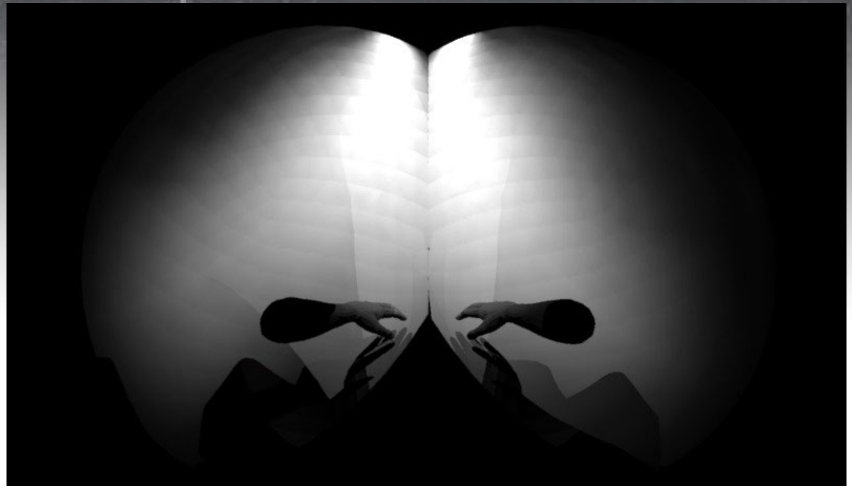
More light is possible if changes are made to housing shape, reflector, and housing color.

xEMU Lamp/System Light Intensity Analysis



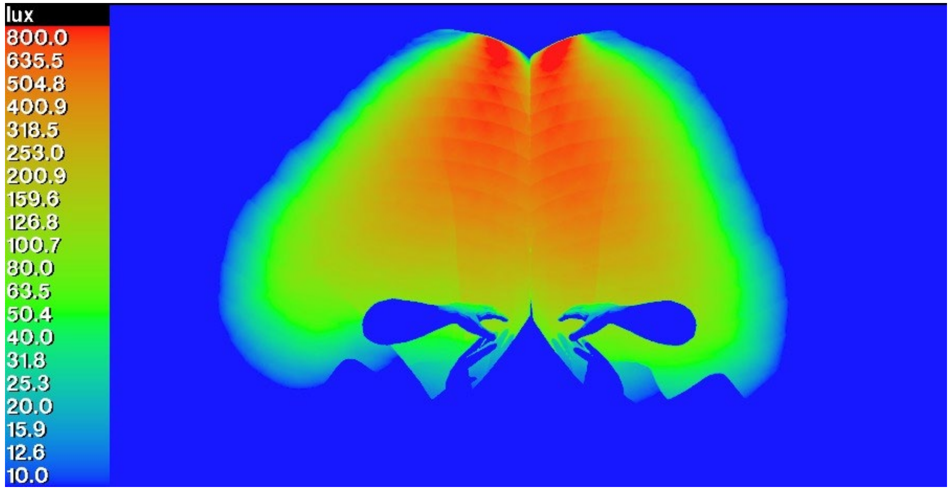
Lighting setup for reach envelope lighting views.

- Figure
- Helmet with lights
- Reach envelopes



Radiance lighting image. Figure and helmet are hidden to show lighting on reach envelopes. Hands in the view for reference.

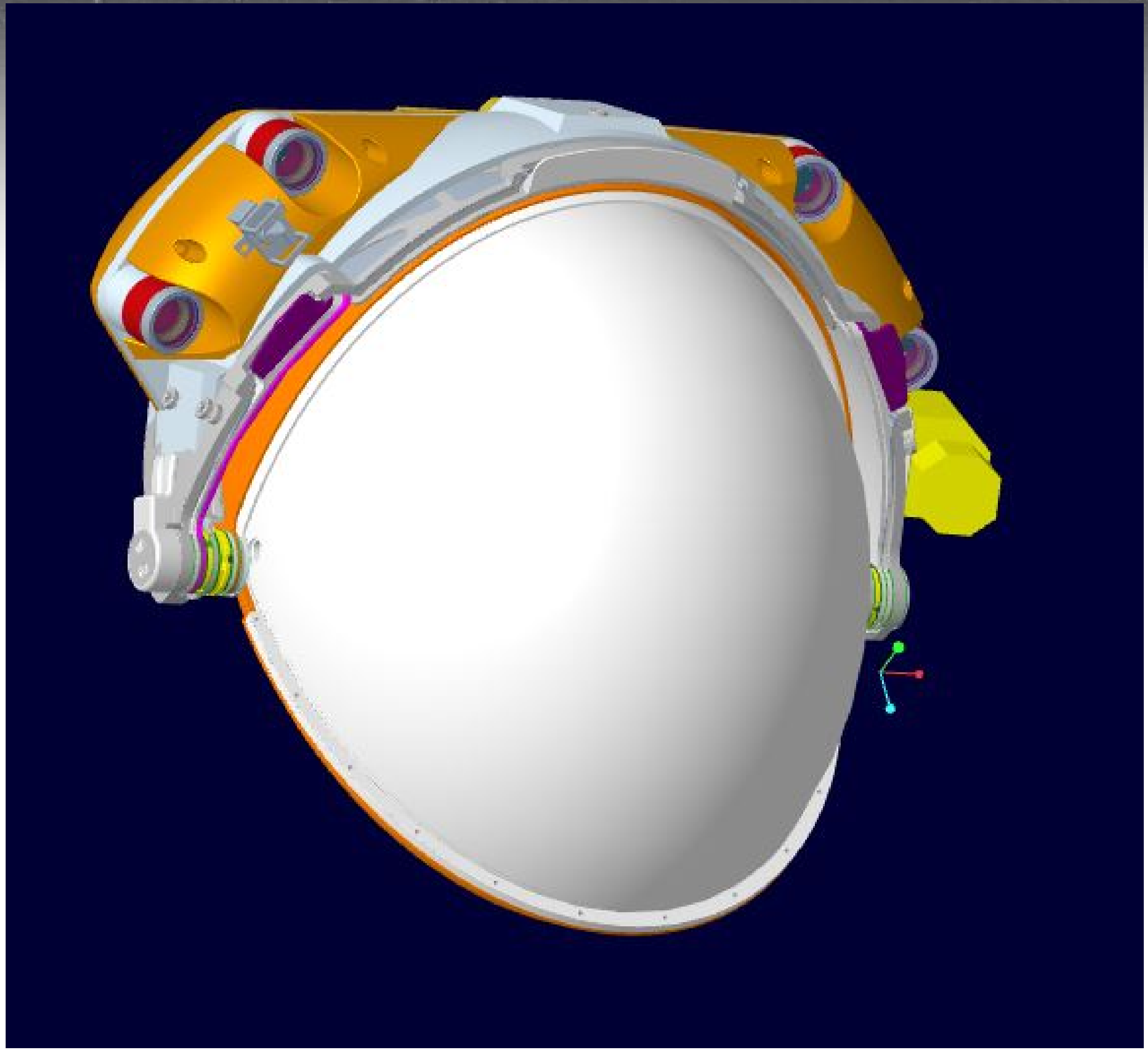
Note: Hidden objects still interact with the lighting environment.



False color lighting image showing amount of light falling on a surface in lux. Colors show the intensity the of light.

Radiance TM

xEMU Lighting System



Backup Slides

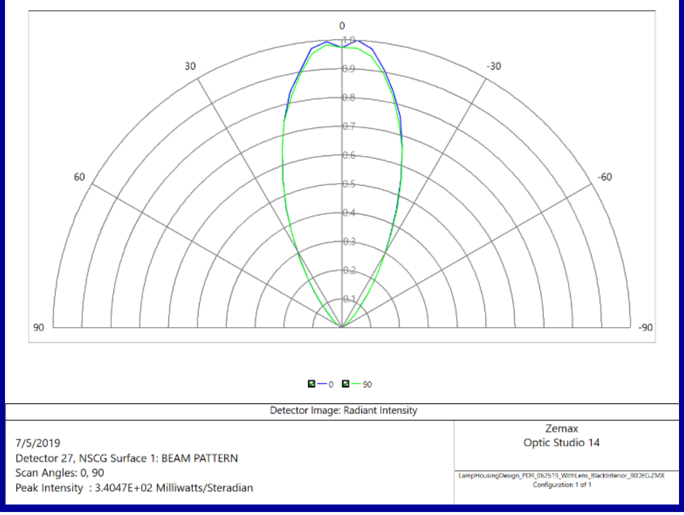
Assorted Detailed Backup Material

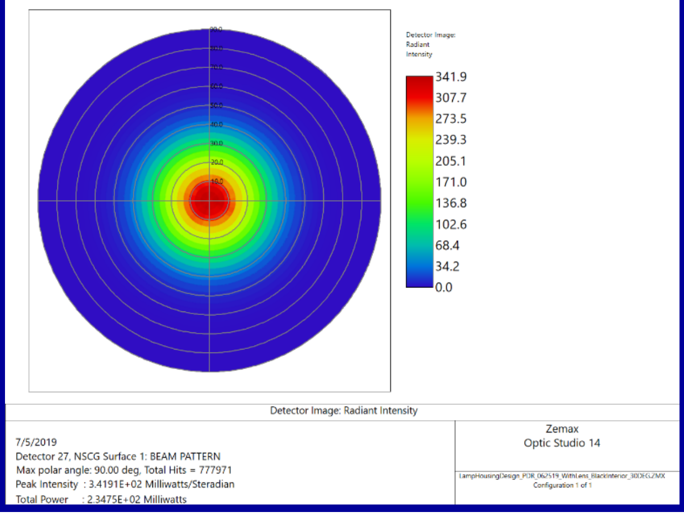
Requirements

Requirement	Design Compliance
[XEMU.FUN.051] WORKSITE ILLUMINATION THE XEMU SHALL PROVIDE EVA WORKSITE ILLUMINATION.	- Helmet mounted lighting assembly. - Energy efficient LED modules. - Worksite illumination has been broken down to work light output and translational light output to accommodate illumination for a large area
[R.LIT.2095] WORK LIGHT OUTPUT THE INFORMATICS LIGHTS SHALL PROVIDE A MINIMUM OF 150 (TBR) LUX AT 500MM FROM TBD EYEPOINT	- ABF has provided worksite/reach envelope data for Z-2 suit - HITL testing to be performed to determine true minimum lux required to perform tasks.
[R.LIT.2085] LAMP CHROMATICITY The Informatics lights shall have a chromaticity that falls within the chromaticity gamut for white light for the Correlated Color Temperature (CCT) range of 2700K to 6500K (TBR) as defined by ANSI C78-377, Specifications for the Chromaticity of Solid-State Lighting Products.	- LEDs were selected to have a color temperature of 4000K
[R.LIT.2085] LAMP COLOR ACCURACY The Informatics lights shall have a score of 90 ± 10 on a color fidelity metric that is appropriate for the utilized lighting technology as designated by the Color Fidelity Metric (Rf) defined by IES TM-30 methodology.	- LEDs selected contain a score of 90 on the color fidelity matrix - Color accuracy is crucial when performing gold salt tablet test to detect hydrazine prior to entering airlock
[R.LIT.2100] Translational Light Output The Informatics lights shall provide a minimum of 50 (TBR) lux at 500mm from TBD normal angle	- ABF has provided worksite/reach envelope data for Z-2 suit but has not completed their testing for Z-2.5 suit. - HITL testing to be performed to determine true minimum lux required to translate.

xEMU Lamp/System Beam Patterns

Multiple optical studies were performed to determine an optimal beam pattern shape to minimize entrance of light into bubble while producing good illumination at the target. It was found that 30° Half Angle was the widest tolerance allowed for the beam.



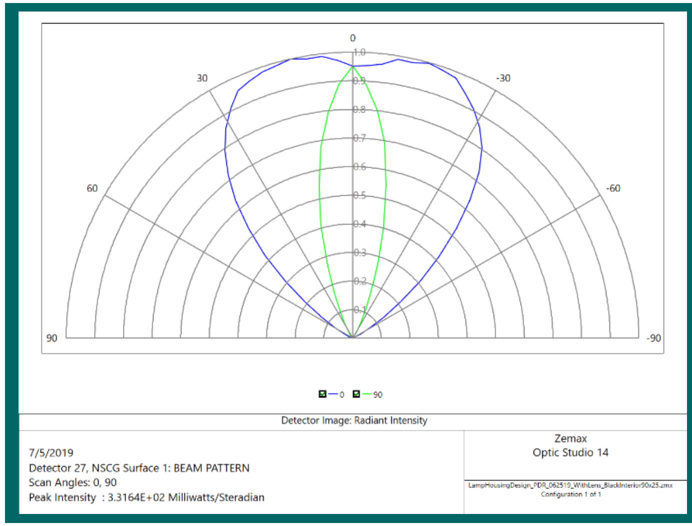


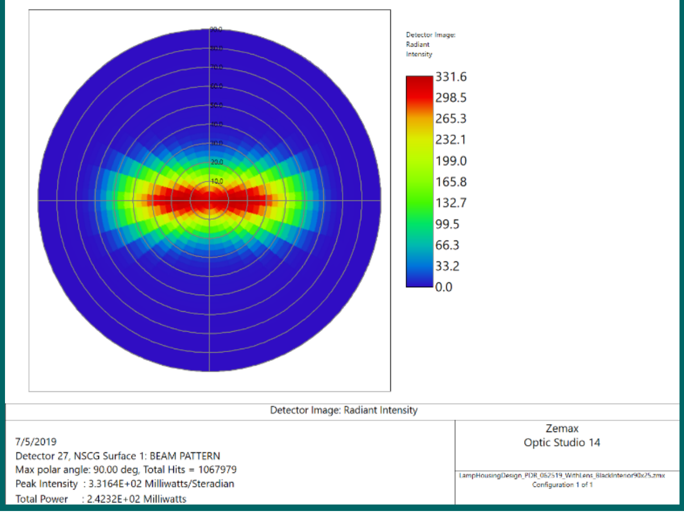
Work Zone Lamp

Beam width ~ 25° Half Angle

This lamp outputs 69.43 lumens

More light is possible if changes are made to housing shape, reflector, and housing color.





Translational Zone Lamp

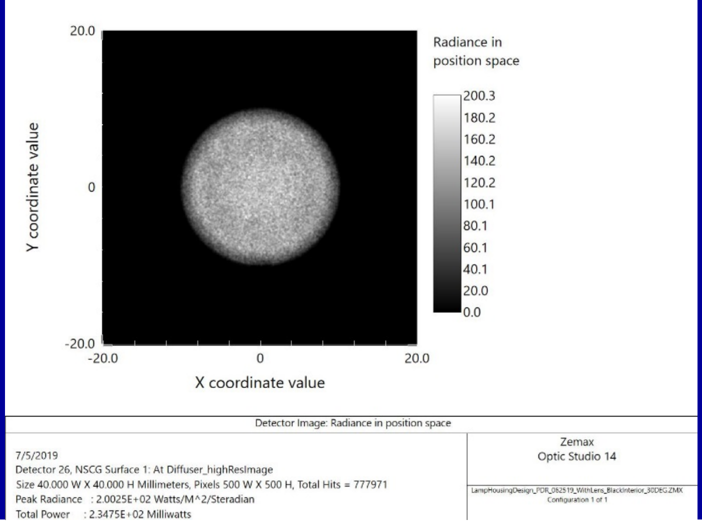
Beam shape is 18 ° x 50 ° Half Angle

This lamp outputs 71.67 lumens

More light is possible if changes are made to housing shape, reflector, and housing color.

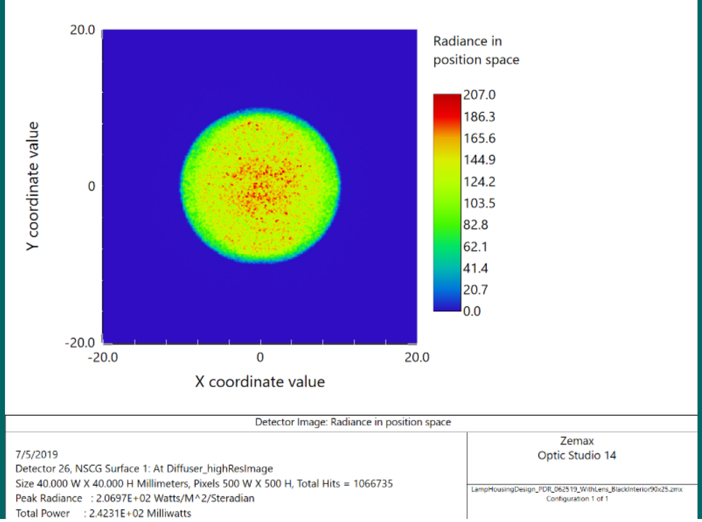
xEMU Lamp Appearance

Providing good illumination while hiding the LED is important. Currently we are planning on using holographic diffusers because of their ability to provide beam shaping and LED hiding features while transmitting more light when compared to standard opaque diffusers. This Zemax model utilizes manufacturer provided scatter data to model beam shaping and diffusion properties.



Work Zone Lamp

The diffuser does an effective job of hiding the LED. The lamp looks very uniform.



Translational Zone Lamp

The diffuser does an effective job of hiding the LED. The lamp looks very uniform.

Due to the narrow but wide beam distribution the lamp appears slightly oblate

Imager Planning and Photogrammetry Detailed Comments (1)

Orion Program

- Does the CM cabin lighting, beginning with Artemis II, which flickers at a high frequency and has several banks and therefore, combinations and associated illuminance levels, cause any banding in the crew cabin video imagery?
- What was going to be the illuminance environment during the Ascent Abort 2 Crew Module / Sep Ring separation?
  - A forward-looking sep-ring camera was placed in view of the CM heat shield (upon which was affixed tracking targets), with the intent of supporting quantified performance analysis of the separation event –BUT
    - The stakeholders wanted sep-ring camera imagery of the CM from its initial position out to 8 feet of separation.
    - The chosen camera could not operate in autoexposure mode due to the expected rate of change in illuminance.
    - Review of Pad Abort imagery indicated that the heat shield would be about 2X more luminous than water clouds in the background receiving direct morning sunlight.
      - It was luck that a couple of views of heat shield surface were captured (in spite of the billowing plumes) in images in which background water clouds were present
      - The above constraints led to a careful choice of lens aperture and of a single, fixed exposure time per frame and the careful positioning and pointing of 4 bright DC spotlights at the surface/targets of interest.
      - Photogrammetric targets were chosen so as to have retroreflective cores.
      - It was luck that the illumination needed fit within the electrical power allotment available.
    - The result was a successful imaging through the separation interval of interest and successful photogrammetric assessment of the separation trajectory.

Imager Planning and Photogrammetry Detailed Comments (2)

- What exposure and framerate settings would be necessary for determining the separation pose and position versus time of the forward bay cover (EFT-1, Artemis-1, Artemis-2)?
  - Extensive experimentation in the JSC lighting lab (called the Lighting Environment Test Facility or "LETF") prior to EFT-1 was performed, leading to successful post-flight evaluation of the separation trajectory.
- What setting for the window cameras (i.e. "FTCams") for EFT-1 would be needed for the environment of (initial) pure darkness through Ogive clearance during the Launch Abort System jettison?
  - Extensive experimentation in a Lockheed Martin lab as well as analysis based on knowledge of the imaging chip led to good mission imaging of the inside of the Ogive from LAS jettison initialization through Ogive clearance of the CM.
- What settings for cameras for which exposure control is limited are necessary for the Service Module inspections during Artemis 1 and 2?
  - Experimentation using sunlight-level illuminance from extraordinarily bright flashlights upon "paper-dolls" of previsualized and appropriately-scaled spacecraft graphics has given good insight into proper setting of camera lighting response parameters that are available for control.

Imager Planning and Photogrammetry Detailed Comments (3)

- For the heat-shield camera (of very similar purpose/positioning to the AA2 sep ring camera) planned for Artemis-1 and Artemis-2, which has a modest illuminator, what is the appropriate orientation of the spacecraft with respect to the sun to make optimal joint use of the artificial illuminator and sunlight, given a wide spectrum of sun angles that occur over possible reentry dates?
  - Extensively assessed using simulations by the JSC Graphics Research and Analysis Facility (GRAF) lab (w.r.t. solar illumination environment). The GRAF is supported by the same analysts as the LETF.
  - Further assessed using knowledge of the luminous flux from the artificial source.
  - Based upon the above analysis, an appropriate spacecraft orientation for the time of Crew Module / Service Module separation was agreed up by the Integrated Mission Performance team in December, 2017.
  - The above GRAF analysis was also incorporated into a separate lens contamination analysis report in May 2018, which was required because the heat shield camera has some external environment exposure during the time that the vehicle sits at the launch pad. Lens contamination can cause “stray light” to reflect from a lens outer surface onto a chip, when the light sources itself isn’t even in the field of view. The risk that such stray light could interfere with heat shield observation during CM/SM separation was assessed.
- How will cabin cameras peering through Crew Module windows respond to their own glare reflected off multiple window pane surfaces?
- How will external cameras, which view the “spacecraft separation” event, occurring after the big “push” to the moon be assured of collecting images suitable for quantitative assessment of separation performance, given that no deliberate orientation of the spacecraft for favorable solar lighting will be allowed.
  - Top priority for spacecraft orientation is given to radio linkage.
  - To compensate for the lack of control of natural lighting and modest output of artificial lighting from the external camera LEDs
    - Retroreflective targets have been placed on relevant surfaces of structures separating from each other.
    - Exposure bracketing has been programmed for the two external cameras

Imager Planning and Photogrammetry Detailed Comments (4)

SLS Program

- Illumination prediction is currently of great interest to the team tasked with imaging the launch.
- The JSC GRAF lab is providing ongoing consultation to KSC imagery team principals to help ensure that imaging objectives are not missed due to washout from bright plumes, and under exposure in shadowed regions.

Shuttle Program

- The JSC GRAF lab routinely generated illumination-accurate graphics (then used by ISAG) depicting views of the external tank just after separation in orbit for launch date planning.
    - After the Columbia accident, the state of the external tank at separation, as imaged by Shuttle cameras, was of interest to help stakeholders infer whether or not tank insulation might have come off (and hit the Shuttle) during ascent.

Gateway

- Design of the HALO external camera architecture is in work. ISAG has recommended a quantitative assessment of Gateway external material reflectance under expected lighting conditions and resultant impacts to imagery. How much light can we expect in the shadows under the different expected lighting conditions? This would require GRAF support.
- Orion's docking lights are very bright. Will Orion's docking lights "blind" external Gateway cameras if pointed down the docking corridor?