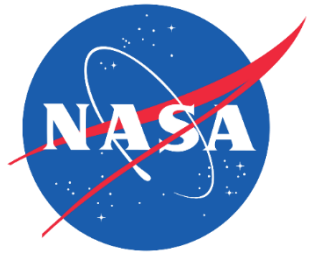
U.S. Coast Guard Boat Recovery Simulation at the NASA Ames Vertical Motion Simulator



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Outline

- Background
  - Motivation & Purpose
  - Small Boat Recovery
  - Vertical Motion Simulator
  - Simulation Goals
- Development
  - Simulation Workflow
  - OTH-IV Cab Design
  - Davit Hook Design
  - Motion Space Analysis
- Operations
  - Sea-state Motion Profile
  - Data Collection
- Conclusions & Discussion

Figure: OTH-IV alongside USCG vessel

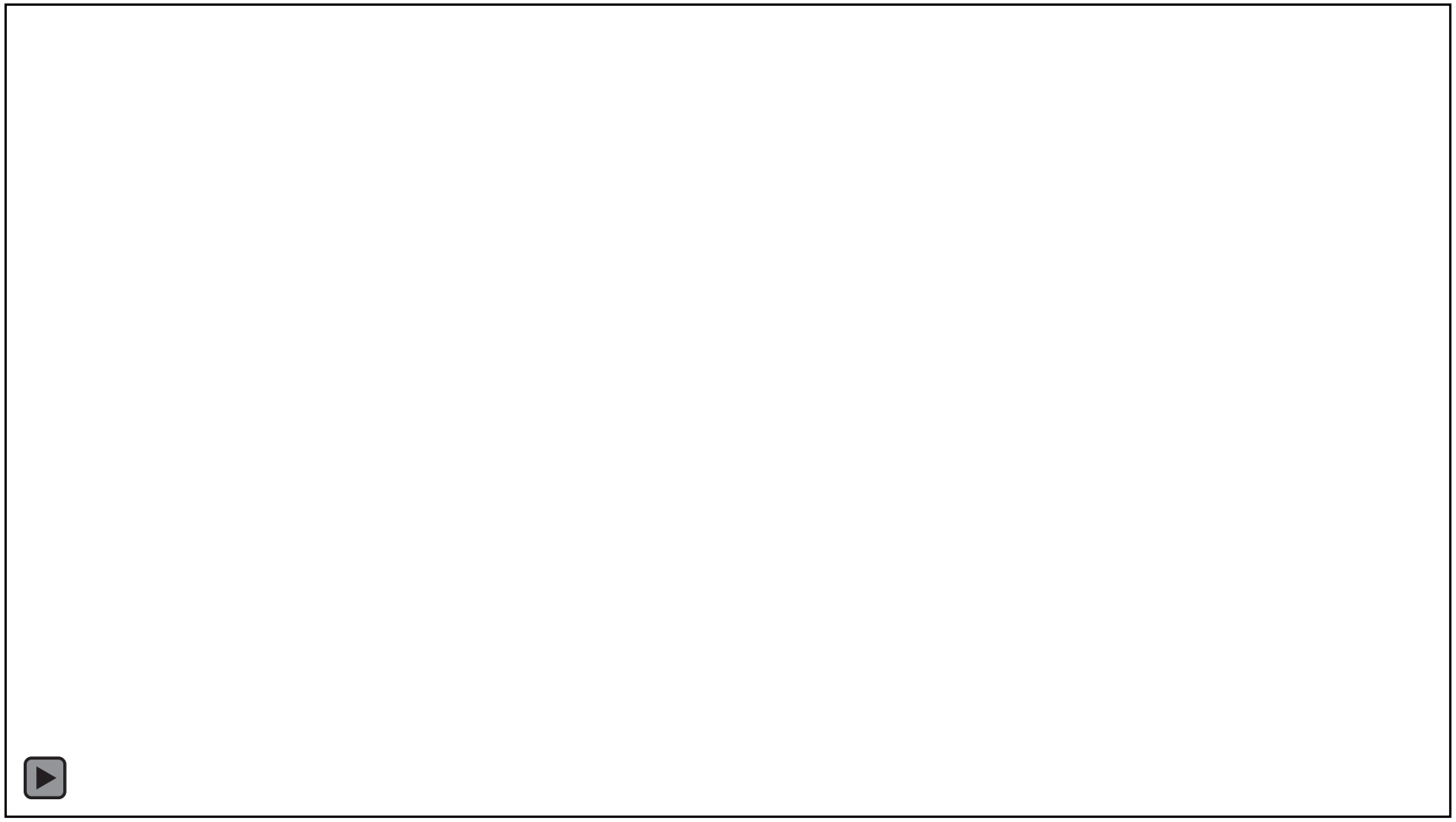
Motivation & Purpose

The U.S. Coast Guard (USCG) recognizes the limitation in human factors evaluation compared to the high-fidelity models used to design boats and mechanical systems for small boat operations.

The USCG collaborated with NASA to develop a motion-based experiment to:

- Evaluate the interaction between human balance and task completion
- Study human performance in different sea-state for the Over-the-Horizon (OTH-IV)

Small Boat Recovery



Source: USCG

Small Boat Recovery

Task elements:

- Crewmember balances and tracks hook
- Davit hook is lowered from cutter boat
- OTH-IV is steered by other crewmember
- Success when davit hook connects to lifting ring

Assumptions:

- Assume a stationary hook
- Assume a steady forward speed
- Ignore stern davit hook

Hazards:

- Fall due to loss of balance
- Impact with davit hook

Figure: OTH-IV side davit recovery

Vertical Motion Simulator

- Located at NASA Ames Research Center, Moffett Field, CA
- Interchangeable Cabs (I-Cab) for different research applications
- Uncoupled six-degree-of-freedom motion

Degree of freedom	Displacement*
Vertical	±30 ft
Lateral	±20 ft
Longitudinal	±4 ft
Roll	±18 deg
Pitch	±18 deg
Yaw	±24 deg

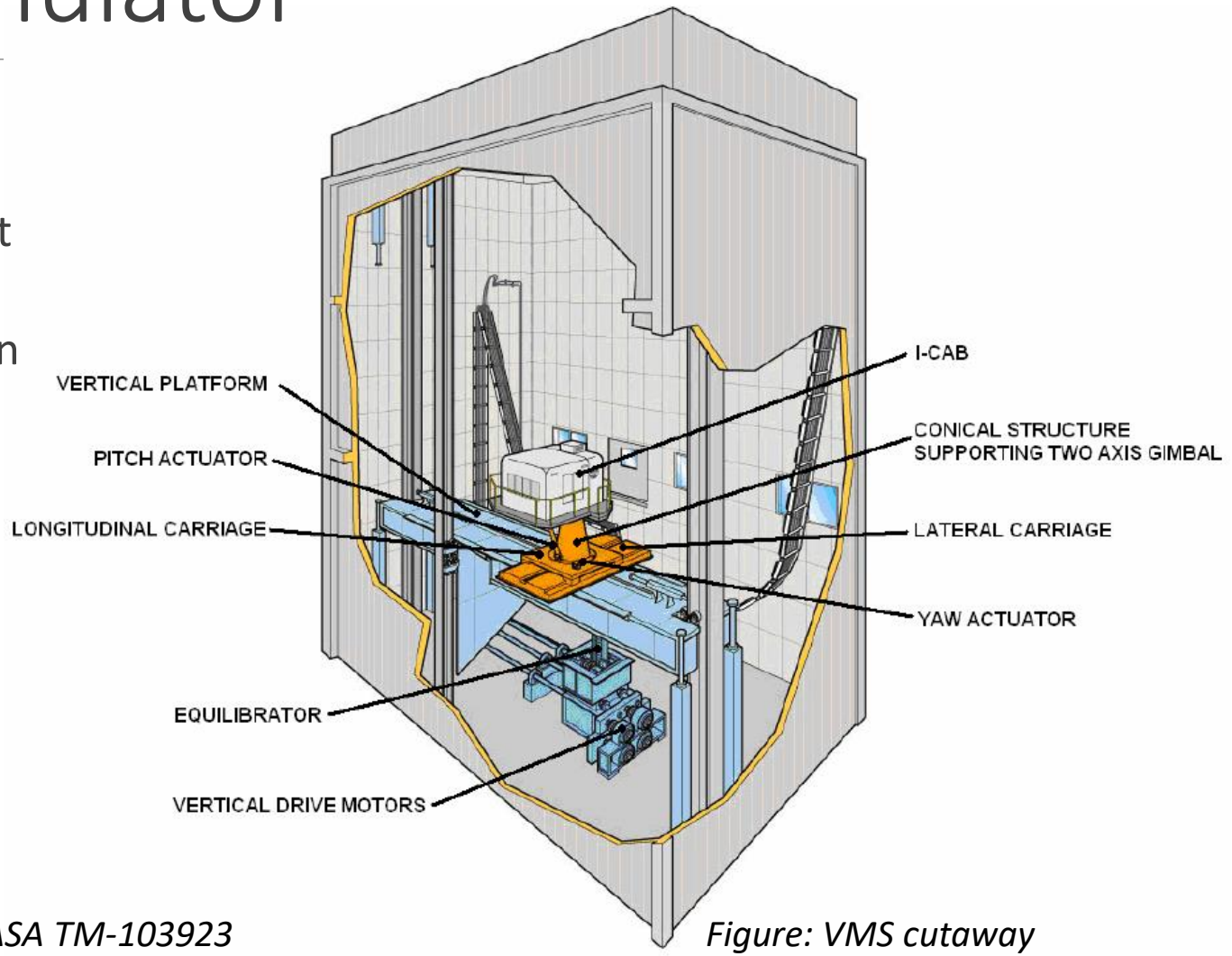
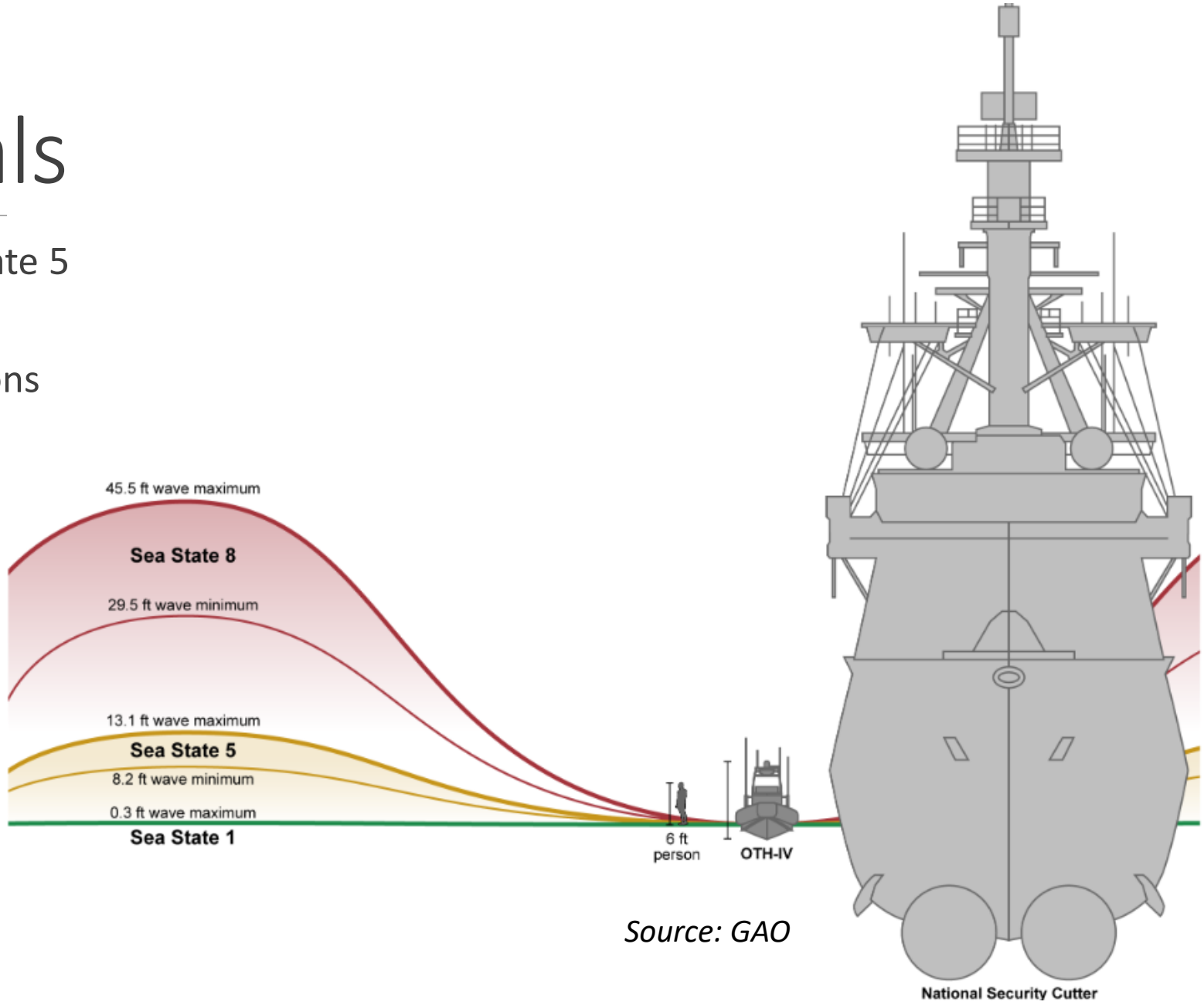


Figure: VMS cutaway

** "Vertical Motion Simulator Familiarization Guide" NASA TM-103923*

Simulation Goals

- Simulate the OTH-IV up to sea-state 5 (13 feet)
- Facilitate repeatable test conditions for human studies
- Ensure a safe environment for participants
- Collect data on the boat recovery task



Source: GAO

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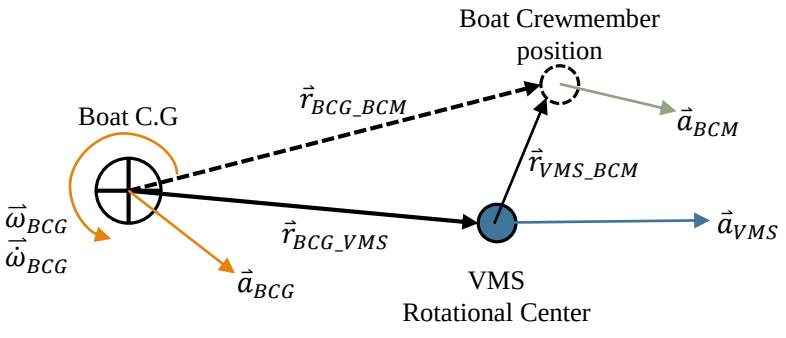
Simulation Workflow

Pre-recorded sea-states,
Rigid body motion



Washout filters & limits

Motion drive system

Vertical Motion Simulator

OTH-IV Cab Design

- I-Cab Modifications
  - Remove canopy, seats, visual system
  - Replicate OTH-IV bow*
  - Enclose the platform
- Fall-arrest system
  - Allow mobility †
  - Prevent falls
- Crane suspended Davit hook

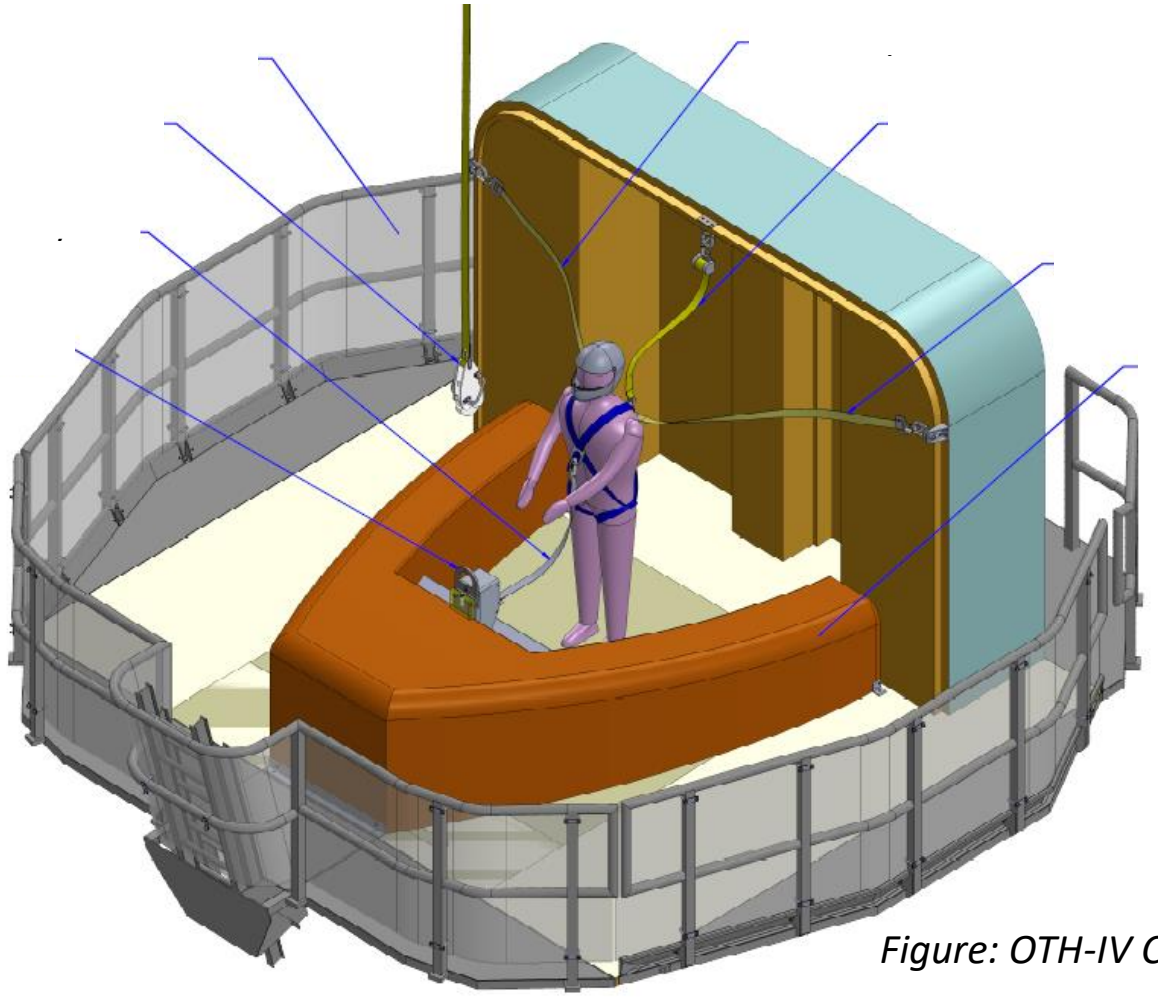


Figure: OTH-IV Cab

** "CB OTH-IV Operator Handbook", USCG*

† "Man-System Integration Standard" NASA-STD-3000

Davit Hook Design

"Limit the risk of human casualty: The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 Joules..." *

Worst-case speed condition: 26.9 ft/sec

- Swinging hook at 5 ft/sec
- Six-axes runaway at full-speed

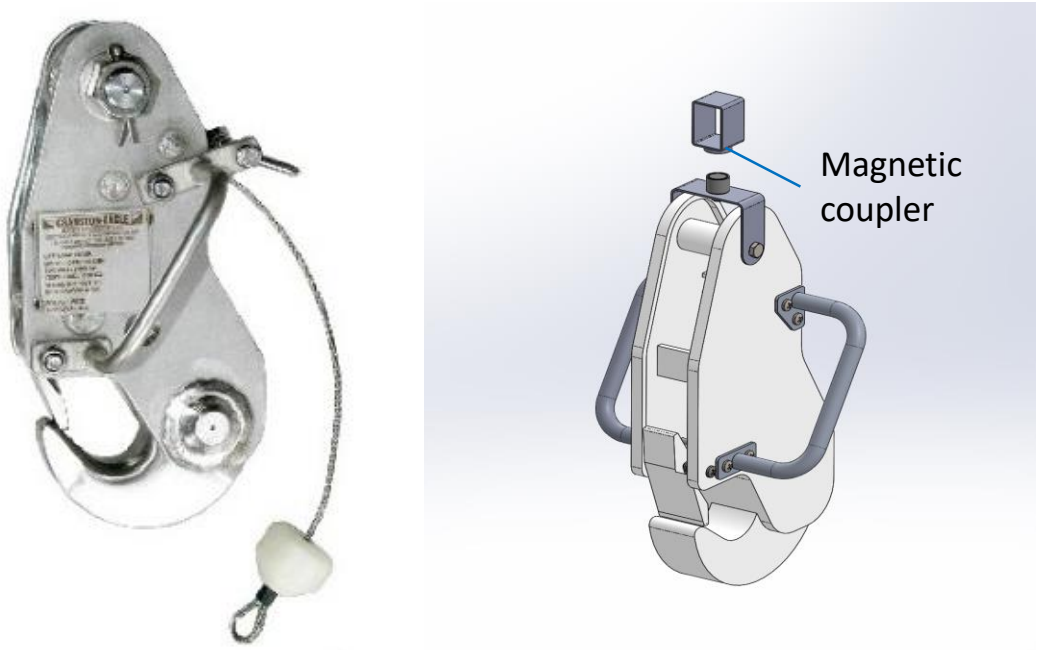
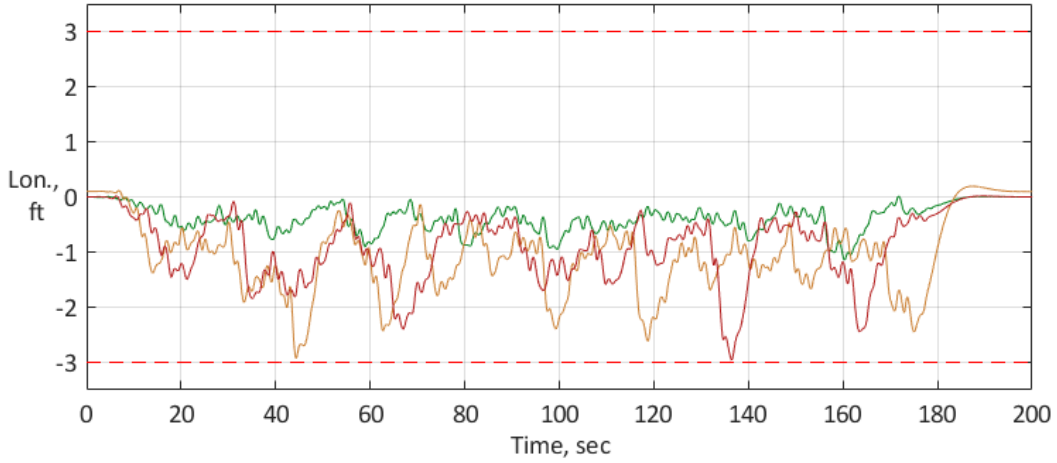
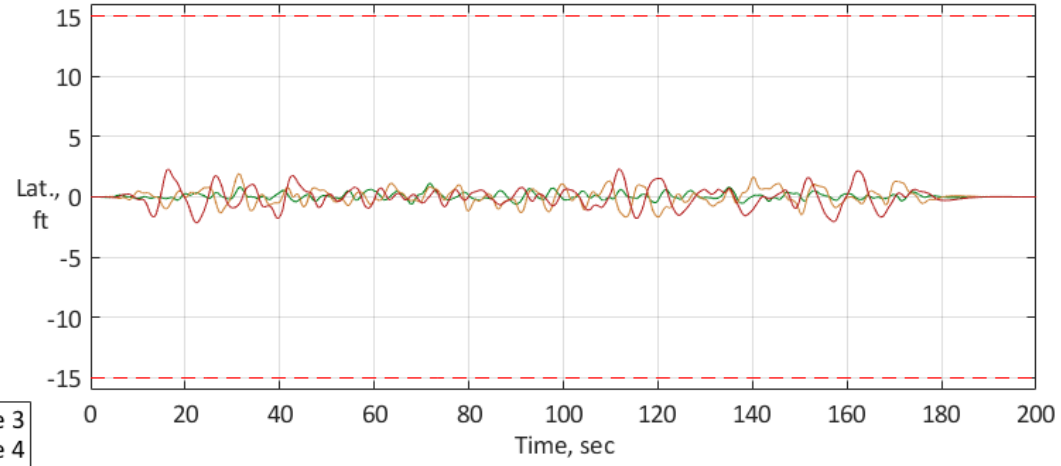


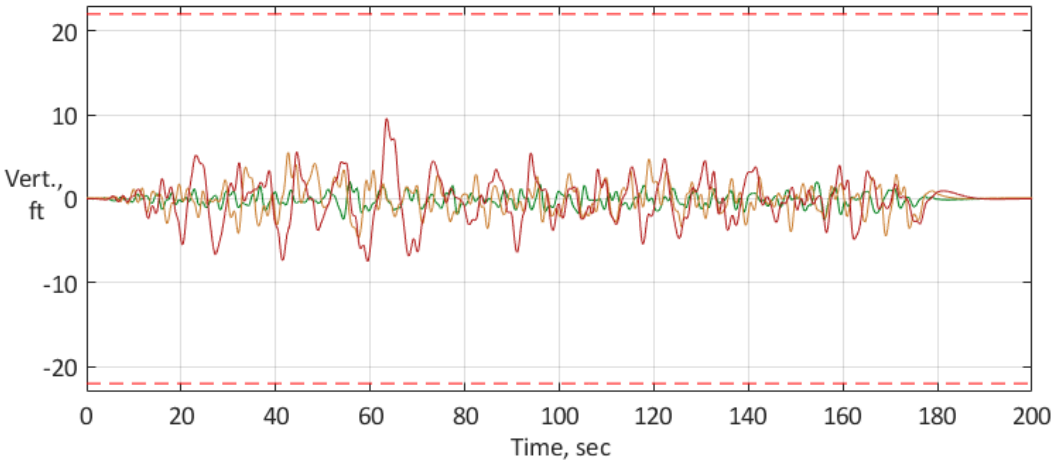
Figure: 24-lb USCG davit hook (left), 1-lb plastic davit hook (right)

** "Process for Limiting Orbital Debris", NASA-STD 8719.14*

Motion Space Analysis







Rotation	VMS Limits
Roll	±14 deg
Pitch	±14 deg
Yaw	±20 deg

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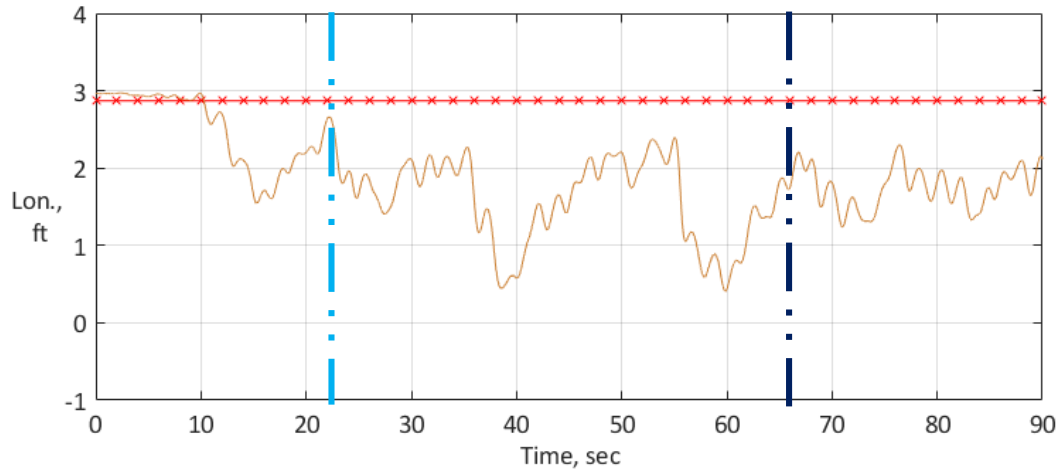
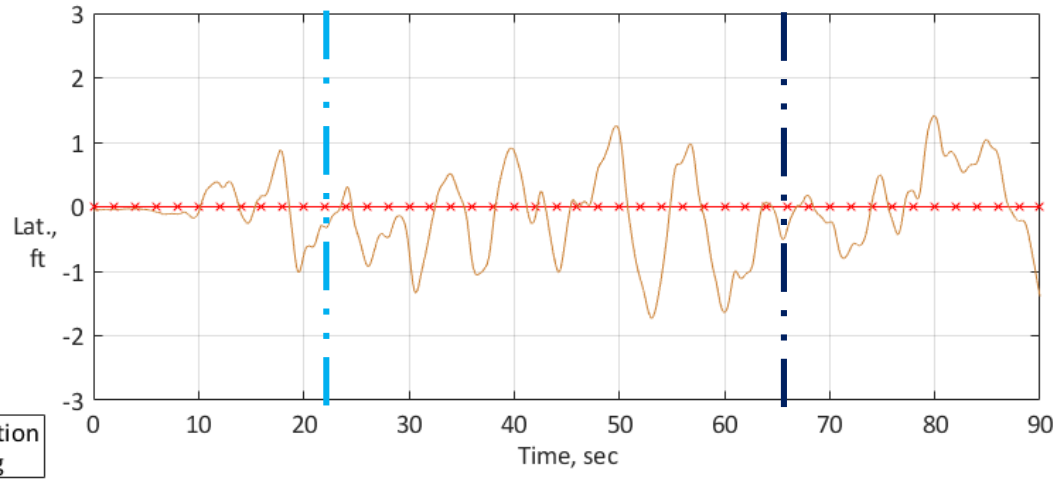
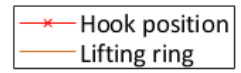
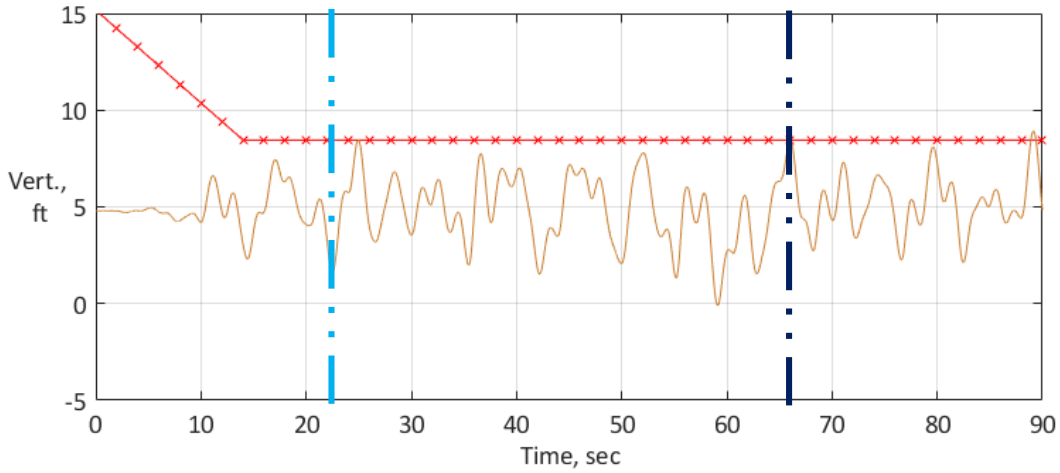
Sea-state Motion Profile

Sea-state 4



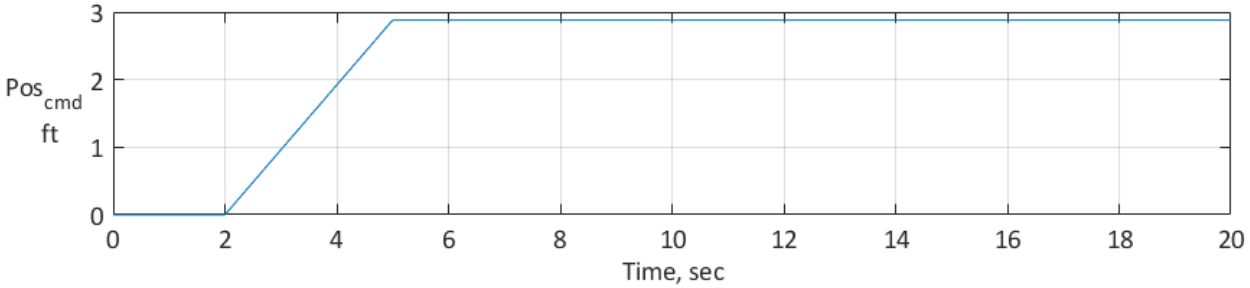


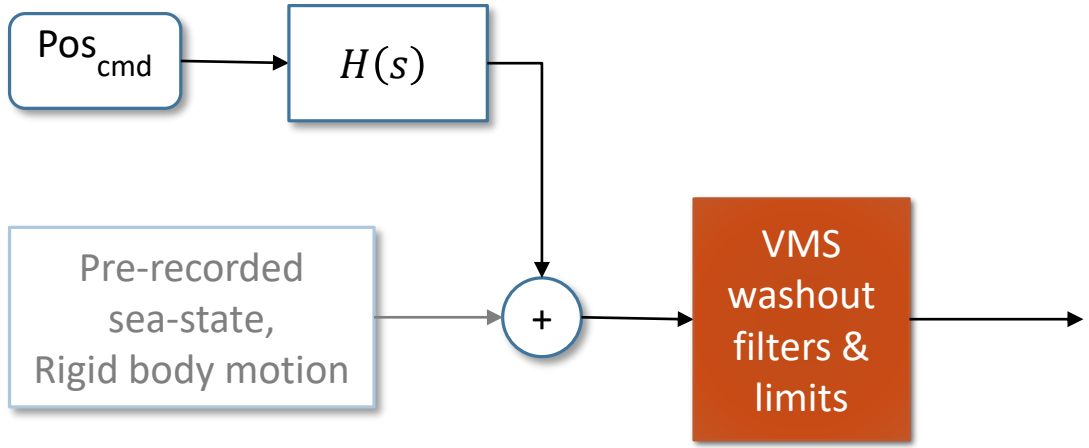




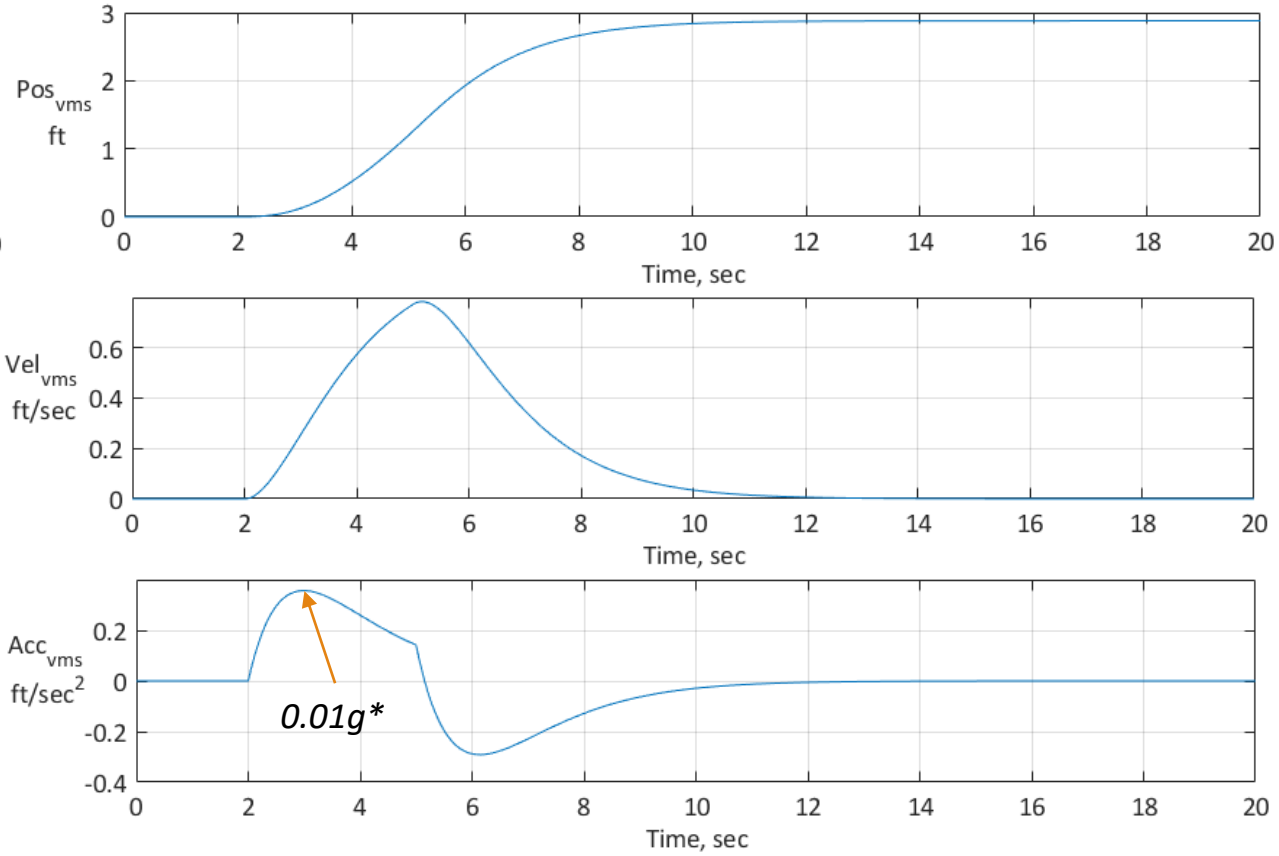
Sea-state Motion Profile

- Define a transfer function to compensate the open-loop motion.





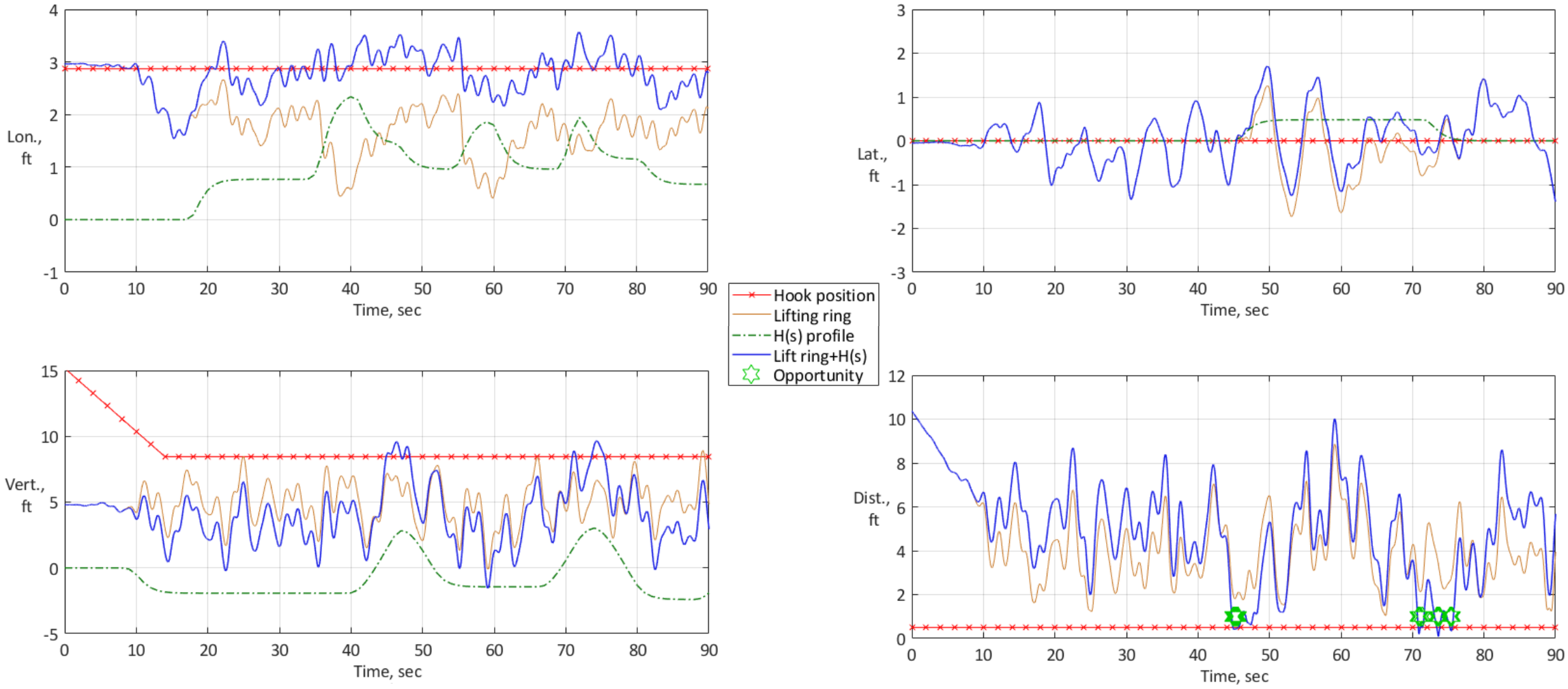
- Control distance between hook and ring with the VMS.



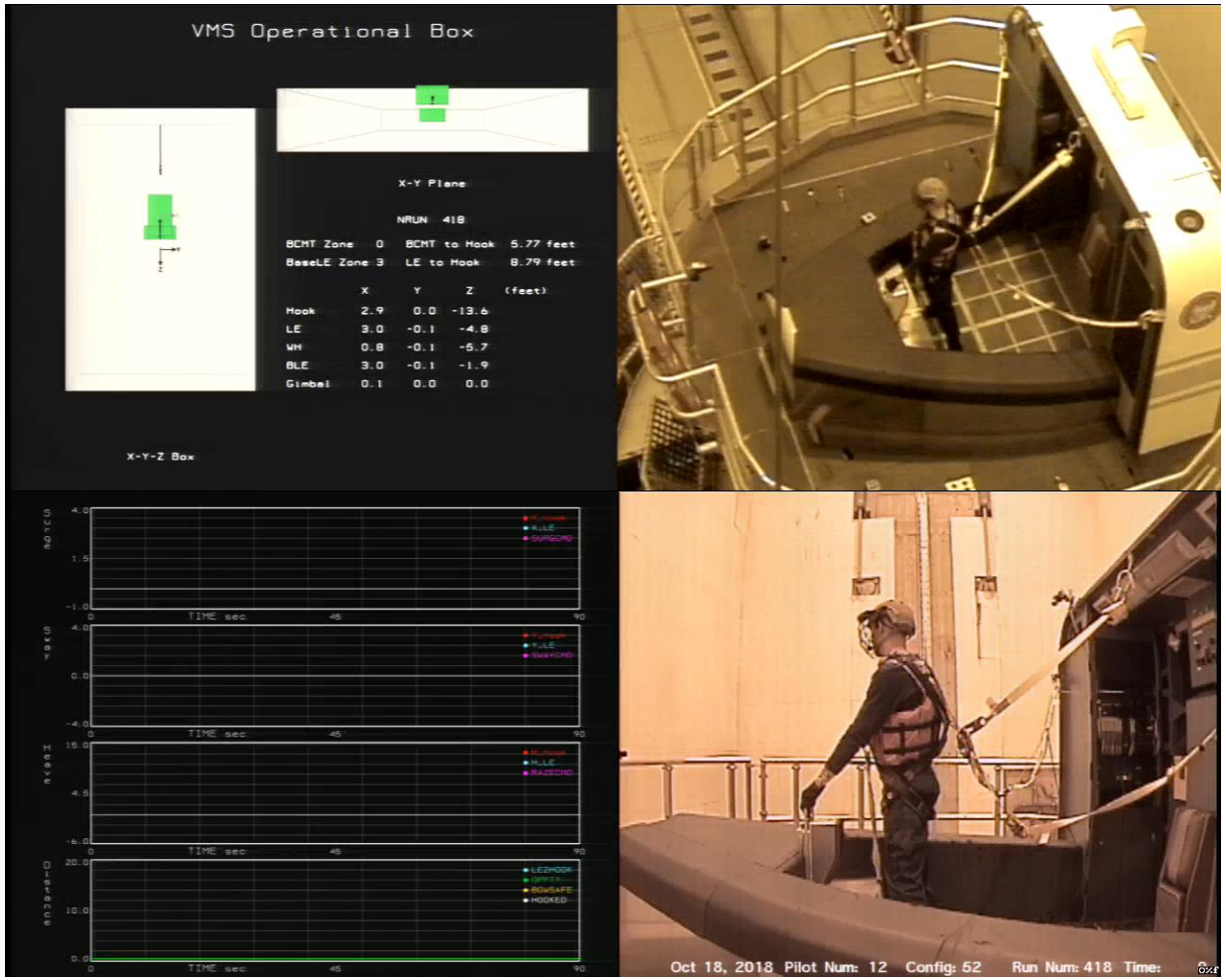
** "The Vestibular System and Human Dynamic Space Orientation, " NASA CR-628, 1966*

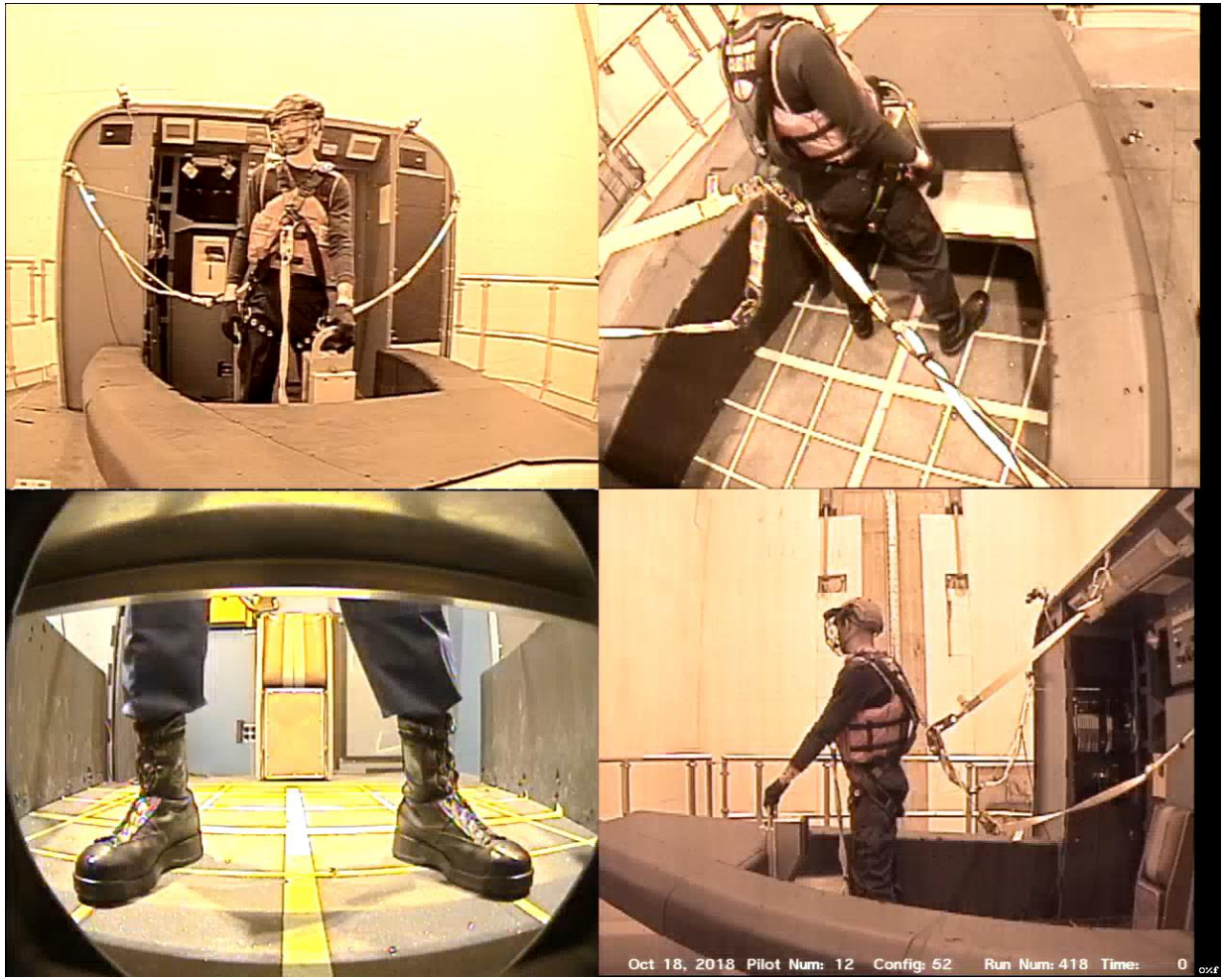
Sea-state Motion Profile

Sea-State 4 (modified)



Data Collection





Conclusions & Discussion

- Proved the VMS can simulate sea-state levels 3, 4, and 5
- Used pre-recorded sea-state data for repeatability
- Designed an OTH-IV cab with safety features
- Provided data and video recordings of certified USCG crewmembers

Extra slides

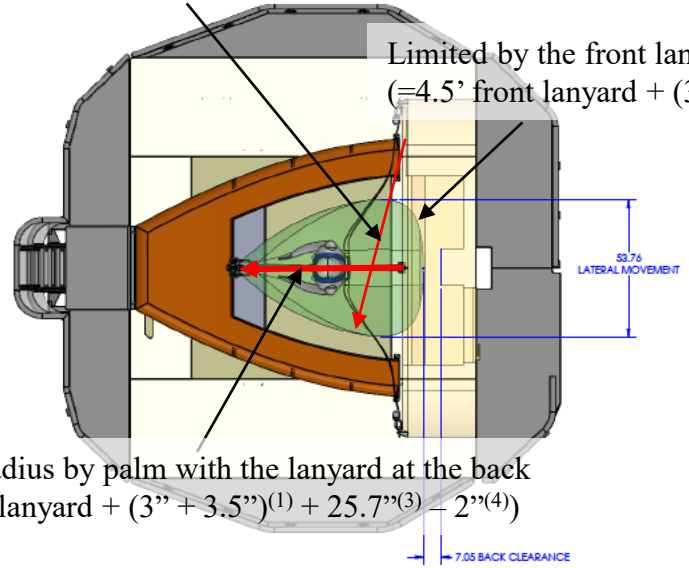
VMS Operating limits

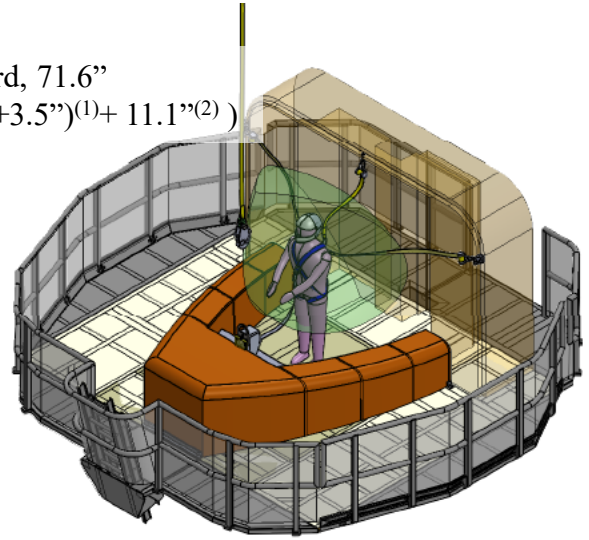
Degree of freedom	Displacement		Velocity		Acceleration	
	System limit	Operational limit	System limit	Operational limit	System limit	Operational limit
Longitudinal	±4 ft	±3 ft	±5 ft/sec	±4 ft/sec	±16 ft/sec^2	±10 ft/sec^2
Lateral	±20 ft	±15 ft	±8 ft/sec	±8 ft/sec	±13 ft/sec^2	±13 ft/sec^2
Vertical	±30 ft	±22 ft	±16 ft/sec	±15 ft/sec	±22 ft/sec^2	±22 ft/sec^2
Roll	±0.31 rad	±0.24 rad	±0.9 rad/sec	±0.7 rad/sec	±4 rad/sec^2	±2 rad/sec^2
Pitch	±0.31 rad	±0.24 rad	±0.9 rad/sec	±0.7 rad/sec	±4 rad/sec^2	±2 rad/sec^2
Yaw	±0.42 rad	±0.34 rad	±0.9 rad/sec	±0.8 rad/sec	±4 rad/sec^2	±2 rad/sec^2

Mobility of the BCM

Bust radius by the side lanyard
89.6” (=6’ side lanyard + (3” +3.5”)(1) + 11.1”(2))

Limited by the front lanyard, 71.6”
(=4.5’ front lanyard + (3” +3.5”)(1)+ 11.1”(2))



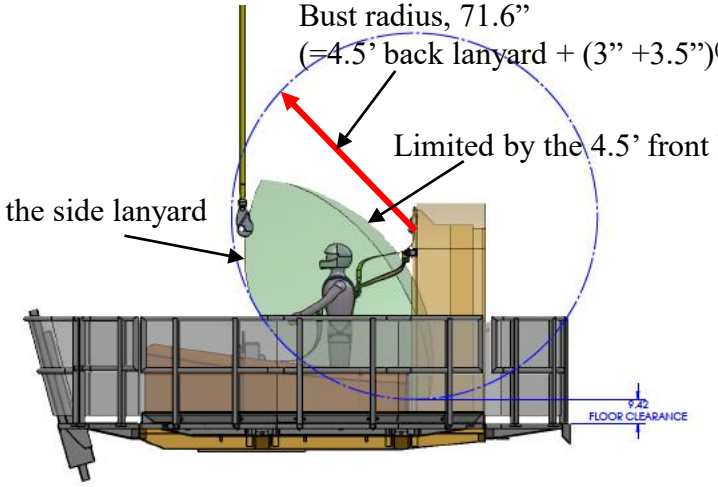


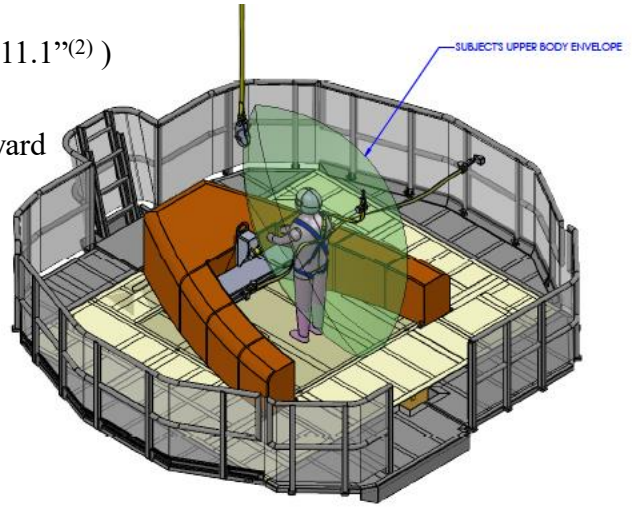
Reachable radius by palm with the lanyard at the back
84.2” (=4.5’ lanyard + (3” + 3.5”)(1) + 25.7”(3) – 2”(4))

Bust radius, 71.6”
(=4.5’ back lanyard + (3” +3.5”)(1)+ 11.1”(2))

Limited by the 4.5’ front lanyard

Limited by the side lanyard



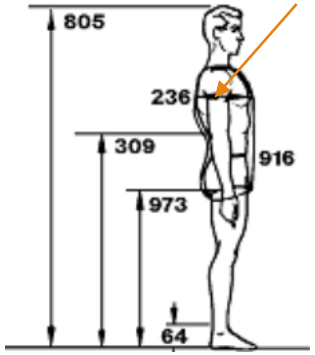


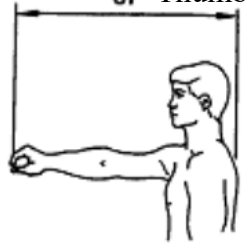
(1) 3”+3.5” is added to account for the hook rings attached to the lanyard at both ends
(2) Bust depth, 11.1”, 95th percentile of male [Ref]
(3) Thumb tip, 25.7”, 5th percentile of female [Ref]
(4) Thumb to palm, 2”, estimated

@95th percentile of height [Ref]
Female: 65” (Fig 3.3.1.3-1 1/12)
Male: 74.8” (Fig 3.3.1.3-1 2/12)

Reference
NASA Man-Systems Integration Standards
https://msis.jsc.nasa.gov/sections/section03.htm

Bust depth





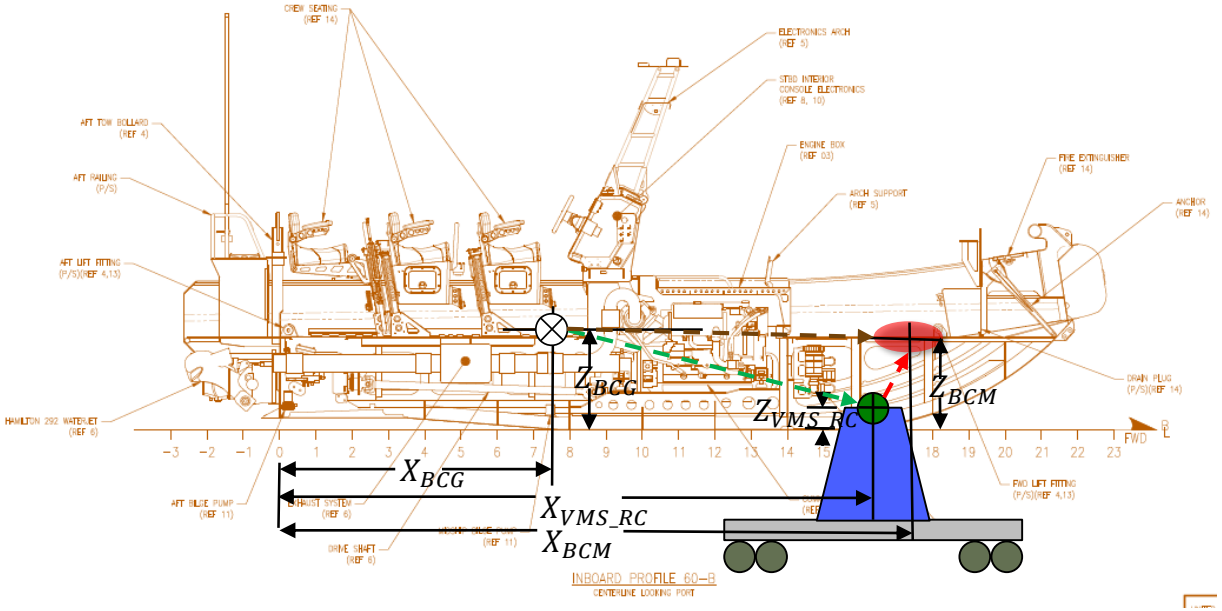
Rigid Body Motion Boat CG to VMS RC

Math Model Source:

US Navy's Large Amplitude Motion Program (LAMP)

Definitions:

a_{VMS_RC} : **Accel. at VMS Rotational Center (VMS_RC)**
a_{BCG} : **Accel. at Boat's CG (BCG)**
$\dot{\omega}_{Boat}$: **Angular acceleration of the boat**
$r_{VMS\_RC/BCG}$: **Position vector of the VMS_RC wrt the BCG**
ω_{Boat} : **Angular rate of the boat**
a_{BCM_RC} : **Accel. at Pilot Station (BCM)**



Rotational Center Drive:

$$a_{VMS\_RC} = a_{BCG} + \dot{\omega}_{Boat} \times r_{VMS\_RC/BCG} + \omega_{Boat} \times \omega_{Boat} \times r_{VMS\_RC/BCG}$$

OTH-IV Performance Load	x (ft)	y (ft)	z (ft)
Boat's CG wrt reference	7.49	0	-2.73
BCM station wrt reference	17.25	0	-2.5
VMS Rotational Center	16.38	0	-0.615
	r_x (ft)	r_y (ft)	r_z (ft)
$r_{BCM/BCG}$	9.76	0.00	0.23
r_{BCM/VMS_RC}	0.87	0	-1.89
$r_{VMS\_RC/BCG}$	8.89	0.00	2.12

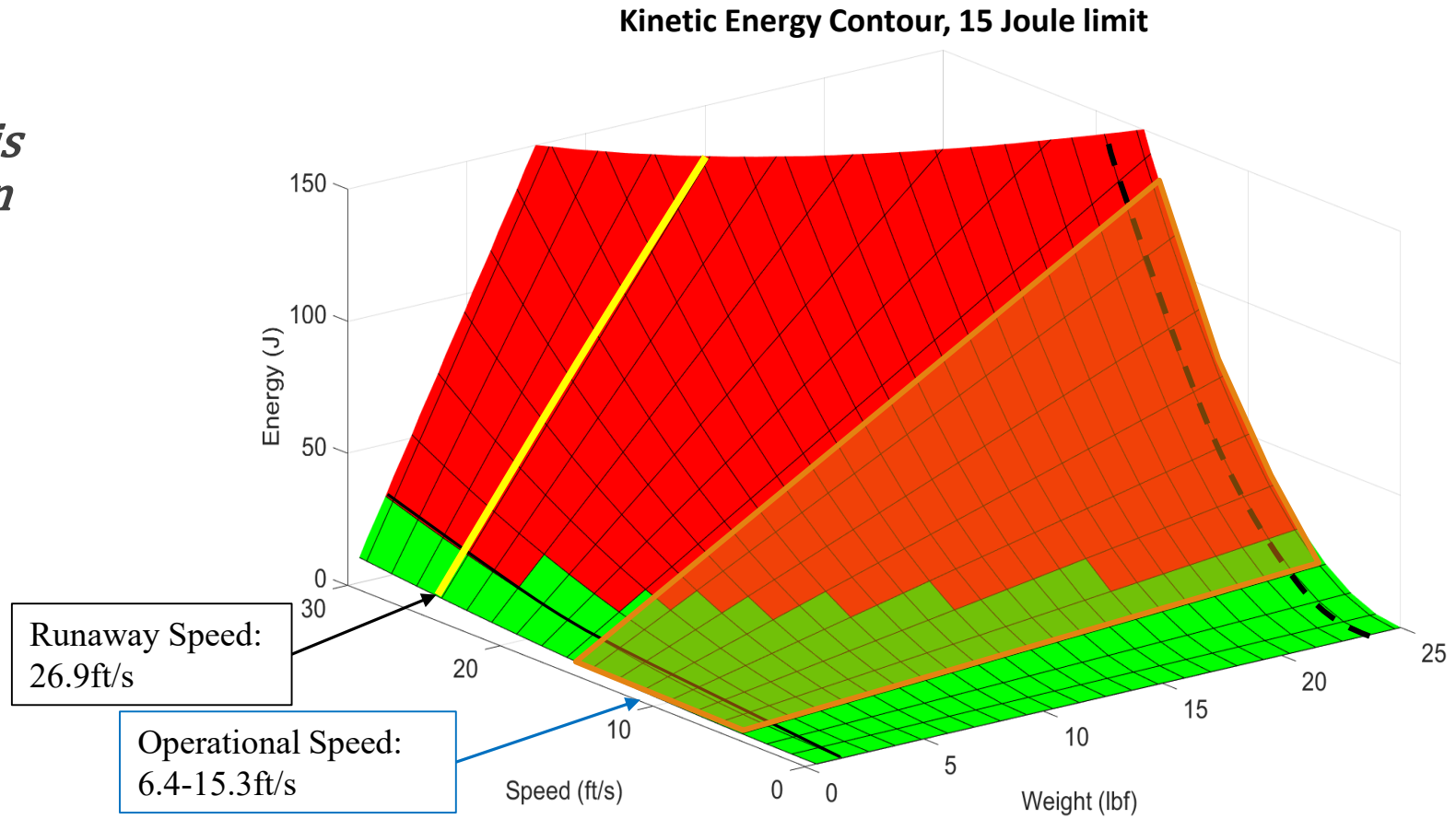
Pilot Station Monitor:

$$a_{BCM\_RC} = a_{VMS\_RC} + \dot{\omega}_{Boat} \times r_{BCM/VMS\_RC} + \omega_{Boat} \times \omega_{Boat} \times r_{BCM/VMS\_RC}$$

Hardware Configuration Impact Risk

NASA-STD 8719.14: "Limit the risk of human casualty: The potential for human causality is assumed for any object with an impacting kinetic energy in excess of 15 Joules…"

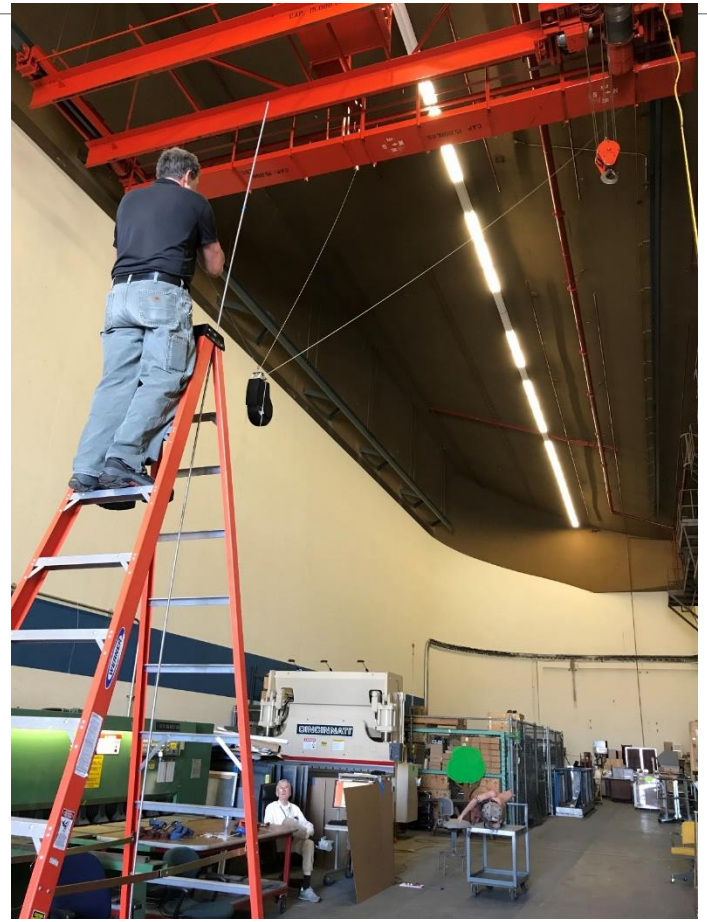
Object Description	Speed (fps)	Energy (Joules)
9mm bullet	1170	467
24lb USCG lifting hook	26.9	366
100mph baseball	146	145
25mph softball	36.7	24.8
1-lb plastic hook	26.9	15.2

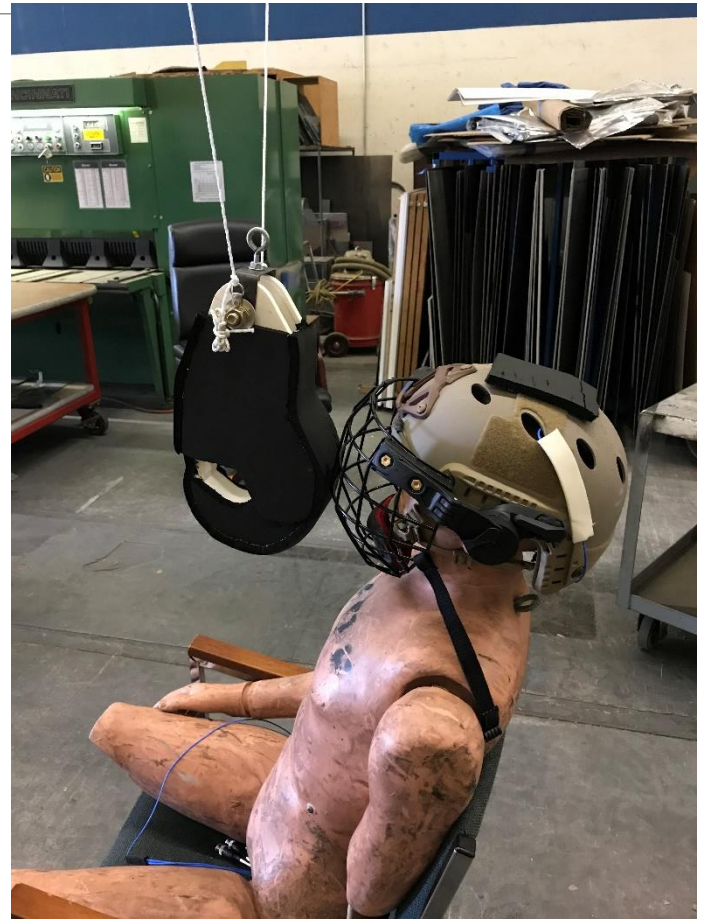


Hazard Analysis: Hook Drop Test Setup

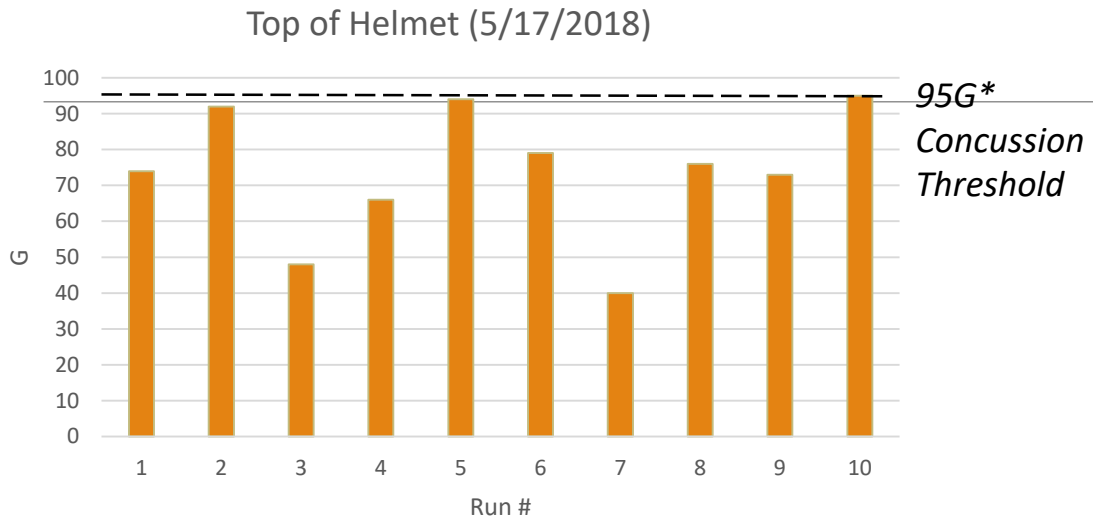
Details

The hook was released from 11.24ft to achieve 26.9ft/s at impact.

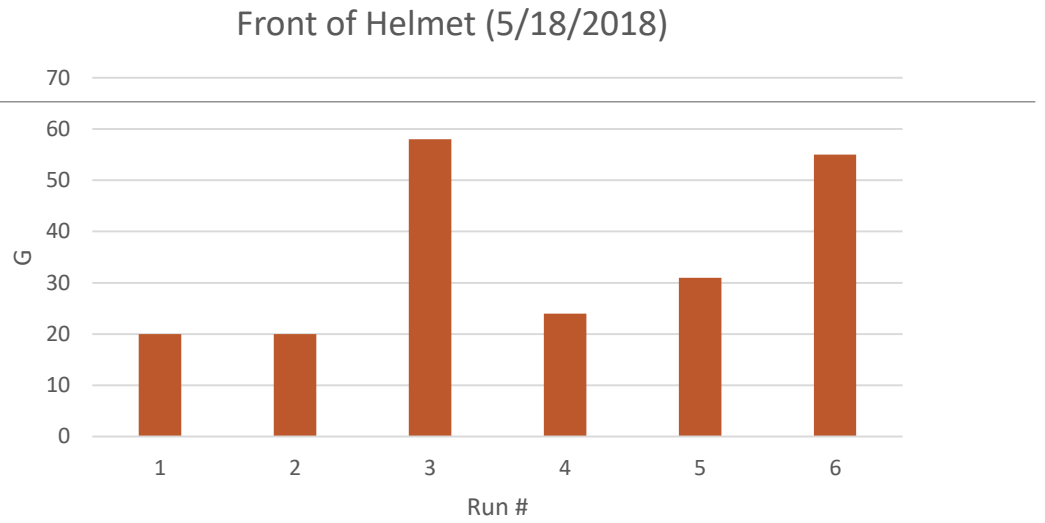


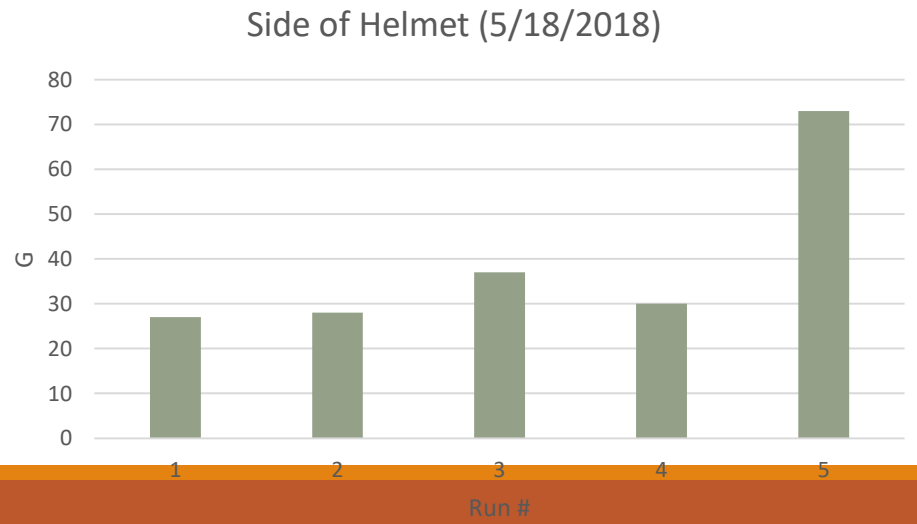


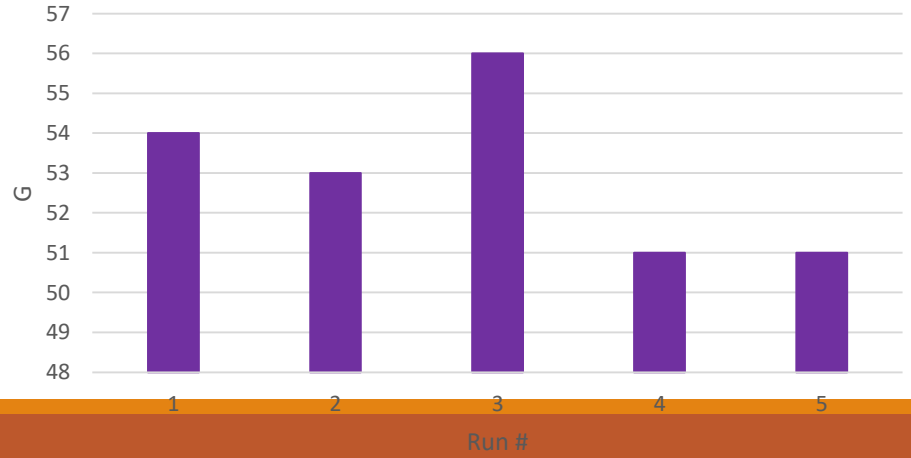
Helmet Drop Test - Results



95G Concussion Threshold*







*Kim Gorgens, University of Denver. https://www.sciencedaily.com/releases/2010/06/100624092526.htm

Vertical Motion Simulator

5 Interchangeable Cabs (I-Cabs) with tailored cockpit for research application.

Figure: I-Cab Installation