System Engineering of Photonic Systems for Space Applications

Michael D. Watson, Ph.D., NASA MSFC
System Engineering Management Office

Jonathan E. Pryor, NASA MSFC
Sensors, Imaging and Optics Branch

Outline

- System Engineering Characteristics
- System Engineering Framework
  - Mission Context
  - System Physics
  - Organizational Structure
  - Policy and Law
- System Engineering of Photonics System Application
  - Space Launch System (SLS) Imagery System
- Summary

System Engineering of Photonic Systems

- System Engineering seeks to obtain Elegant Systems which function
  - Effectively in their intended application and environment
  - Most efficiently as compared to options fitting the system context
  - Robustly in application and operation
  - Avoiding Unintended Consequences

System Engineering of Autonomous Systems

- Elegant System Engineering requires
  - Understanding the Mission Context
    - System Applications
    - System Environments (operational, test, abort, etc.)
  - Understanding the Physics of the System
    - System Interactions with themselves and with their environments are governed by their physics
    - Information Theory provides linkages between physical state representations and actual physical states
  - Managing the organizational influences on system design and the system context influences on the organization
  - Understanding Policy and Law Constraints
    - Environment Protection Agency (EPA) Regulations
    - National Space Policy
    - International Space Treaties and agreements
      - Space Debris, Contamination, Property

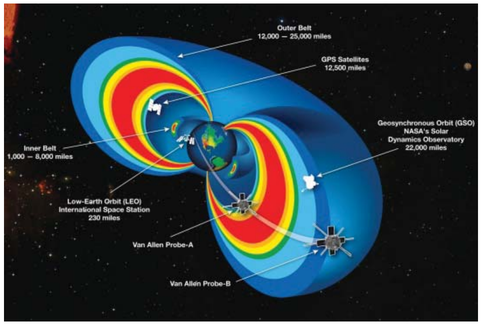
Mission Context

- Establishes Mission Type
  - Astronomy
  - Earth Observing
  - Space Infrastructure (e.g., communication, navigation)
  - Solar Observing
  - Planetary Observing
  - Planetary Lander

Mission Type/ Mission Environmen	Astronomy	Earth Observing	Space Infrastructur	Solar Observing	Planetary Observin	Planetary Landin
Low Earth Orbit	X	X	X	X		
Geo Stationary Orbit	X	X	X			
Lunar Orbit					X	
Lunar Surface			X			X
Interplanetary Space (including Lagrange Points)	X		X	X	X	X
Planetary Orbit			X		X	
Planetary Surface			X			X

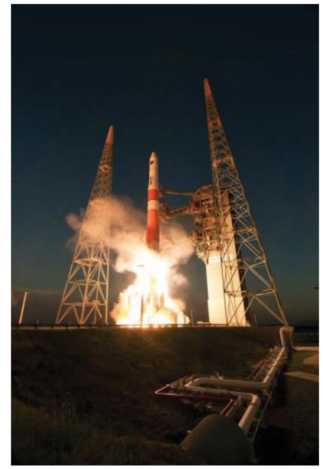
Mission Context: Mission Environment

- Space Environment
  - Thermal
  - Ultra-Violet (UV)
  - Oxygen
  - Space Radiation
- Low Earth Orbit (LEO)
  - Atomic Oxygen
  - Micro Meteorite and Orbital Debris (MMOD)
- Medium Earth Orbit (MEO)
  - Van Allen Radiation Belt
- Geosynchronous Earth Orbit (GEO)



- Lunar Orbit
  - Gravity well not uniform
- Lunar Surface
  - Dust
- Interplanetary Space (including Lagrange Points)
  - Similar to GEO
  - Micro Meteorite
- Planetary Orbit
  - Atmospheric Interactions
  - MMOD
- Planetary Surface
  - Dust
  - Atmosphere

Mission Context: Launch Environment



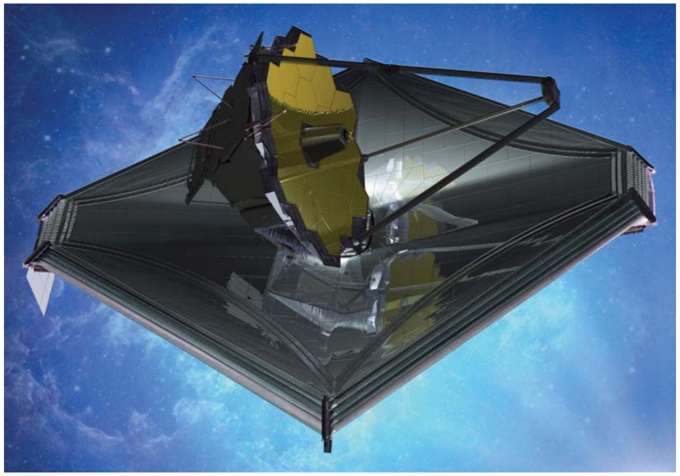
- Launch Site Environment
  - Tropical Environment
    - Humidity
      - 8% - 100% RH
    - Temperature
      - 0 °C – 50 °C operating range
    - High Salinity

- Ascent Flight (US Commercial Launch Vehicle Ranges)
  - Temperatures can approach 50° C – 95° C due to aero thermal heating
  - 130 -140 dB acoustic environment
  - 3000 – 7000 g shock environment

Optical System Physics

- Optics integration into the launch vehicle or spacecraft bus is driven by geometrical stability
- Optical Transfer Function (OTF) captures the effects of the vehicle interactions and the environmental interactions with the optical system
  - $\iint_{-\infty}^{\infty} \psi_{obj} s_f dxdy$
  - The spatial filter, s_f, represents the optical system and is driven by:
    - Thermal gradients
    - Vibrations
    - Mechanical misalignment
    - Contamination (outgassing, dust)
  - From within the optical system, vehicle interactions, and the mission environment

Optical System Physics



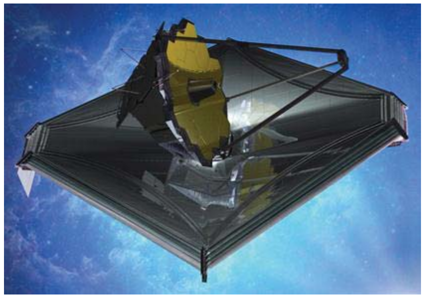
- Pupil function, p_f, is affected by
  - thermal expansion (α_v)
  - Heat transfer rate ($\dot{Q}$)
  - Temporal vibration (d(t))
  - Shock (α_{shock})
- Thus, $pf = f(\lambda, \alpha_v, \dot{Q}, d(t), \alpha_{shock})$
- Contamination
  - Can induce intensity variations or blockages within the pupil function
  - Can induce aberrations on the image plane

Optical System Physics

- Downlink of data
  - Digital Effects
    - Bandwidth
    - Storage Size
    - Gibbs Phenomena
  - Leads to slight misrepresentations of actual object state

Organizational Structure and Information Flow

- Optical system design, development, and testing is the responsibility of the Optical Engineer
- System Engineer is responsible for engineering of the optical system interactions with the launch vehicle or spacecraft bus and the environment
- The Optical Engineer must interact and communicate with other disciplines in an effective manner
  - Understand and participate in vehicle/bus decision structure
  - Ensure supporting disciplines understand the importance of optical tolerances
    - Translate optical tolerances/sensitivities in other disciplines terms
    - 1 mil = .001” ≠ 1 μm (1 mil = 25.4 μ or 1 μm = .0394 mil)
    - Minute movements (thermal, shock, vibration) can make a large difference in optical performance
- Relationship varies with mission type
  - Is the spacecraft bus designed for the optical mission?
  - Are the optics in support of a broader mission?



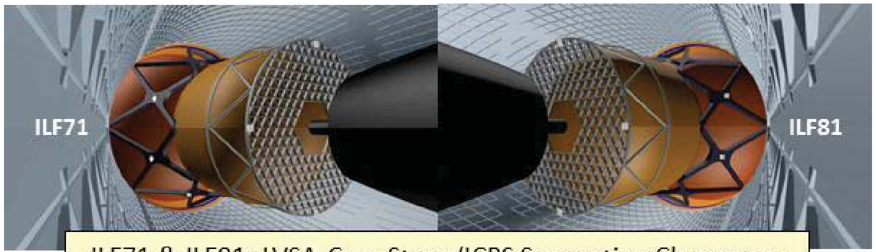
Policy and Law

- National Environmental Policy Act (NEPA)
  - Environmental Protection Agency (EPA) Regulations
  - Executive Order 12114
- National Space Policy
- International Space Treaties and agreements
  - Outer Space Treaty: United Nations' Treaty of Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies
    - Planetary exploration conducted "so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter."
- Applicability depends on Mission Context

Space Launch System (SLS) Imagery System

- Mission Context
  - Support to the launch vehicle
  - Provide video data for analysis of separation tracking events and identification of any debris anomalies or physical malfunctions
  - Focus on events only identifiable from video data
  - Video data fit within the launch vehicle telemetry bandwidth

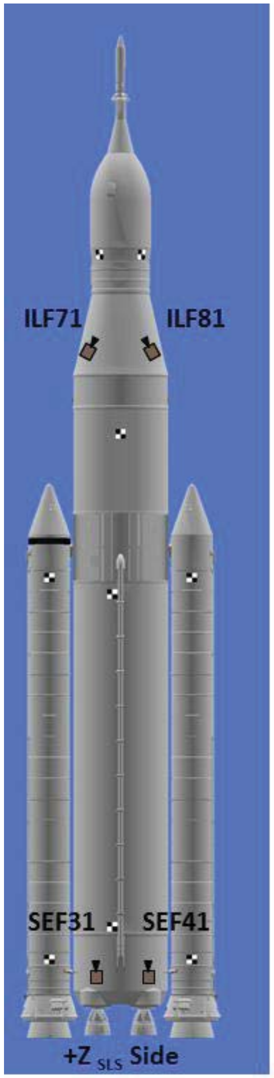
SIA51 & SIA61: Liftoff Vehicle Integrity, Booster Separation for Re-contact



ILF71 & ILF81: LVSA-Core Stage/ICPS Separation Clearances

Space Launch System (SLS) Imagery System

- Optical System Physics
  - System Design
    - Camera system selection based on
      - Image Quality
      - Detector
      - Output Data Type
      - Low-Light Resolution
    - Data buffers to manage data flow and optimize bandwidth utilization
    - Camera Location
      - View of identified areas of interest
      - Mounting location on continuing Stage
      - Sets
        - Camera Angle
        - Field of View
        - Image Size (magnification) based on spatial distance from object
        - Resolution (aberration limits)
        - Depth of Focus
      - CAD is useful for vehicle integration



Space Launch System (SLS) Imagery System

- Optical System Physics
  - System Design
    - Housings
      - Critical design to ensure stability in the flight environment
      - Tightly coupled with the vehicle structure
      - Protect optical system from aerodynamic effects, thermal, shock, and vibration
        - Preserve optical performance
        - Prevent optical system damage

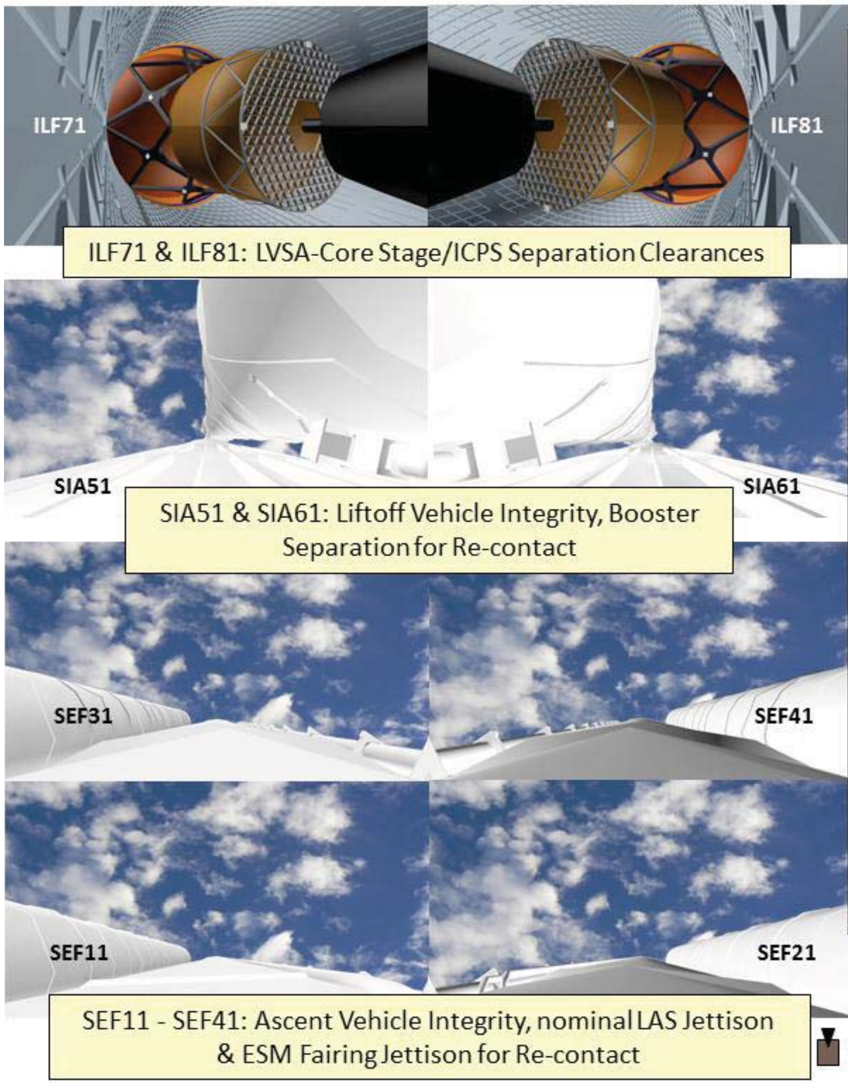
Space Launch System (SLS) Imagery System

- Optical System Physics
  - System Design
    - Image Jitter
      - Time varying spatial motion
        - J0(p,kx,ky)
      - Imaging is not high resolution
        - Identify and track objects of specified size only over a few frames
      - Jitter can be minimized by
        - Minimizing exposure time (image capture) time
          - Minimizes spatial movement of camera during capture
          - Depth of Field requirements also drive aperture/ISO settings
        - Mechanical design
          - No moving lens parts (i.e., auto focus, fixed aperture)
          - Noise dampening layer between components
          - Firmly mount lens and camera within housing

Space Launch System (SLS) Imagery System

- Optical System Physics
  - System Design
    - Data System
      - High quality image compression necessary to fit into vehicle telemetry stream
      - Bandwidth must be shared with other systems
      - Cabling must operate in launch environment
        - Protect connections from vibration/shock induced degradations
        - Minimize signal drop over length
      - Controller
        - Camera on/off
        - Data Flow
        - Illumination components
      - Electrical power conversion from vehicle electrical power system

Space Launch System (SLS) Imagery System Design

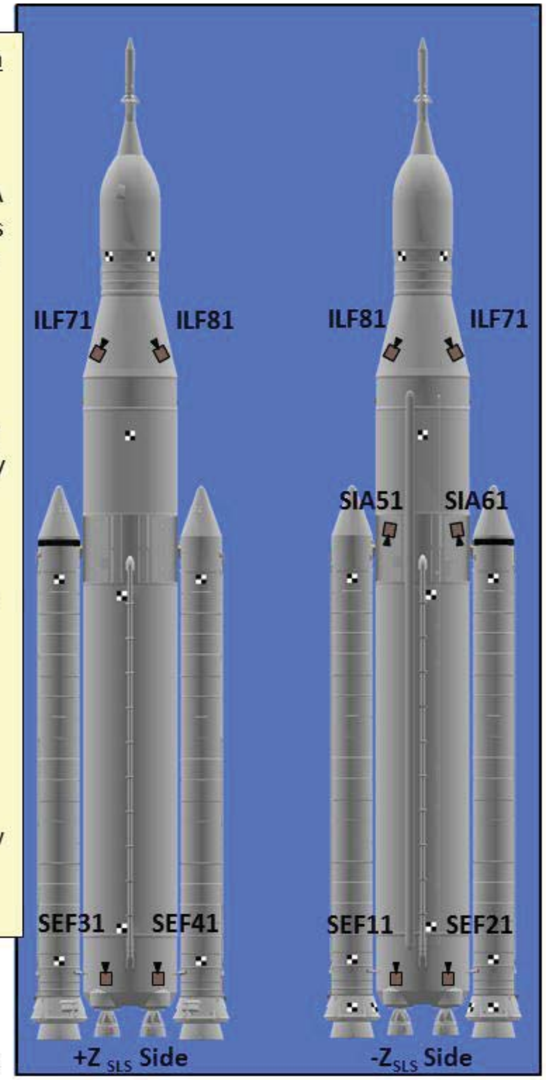


Vehicle Imagery System
- Six cameras on Core Stage OML
- Two cameras with lighting Internal on LVSA
- High Contrast Markings on Core Stage, Booster and ISPE

Provide Imagery of Critical Events:
- Liftoff Vehicle Integrity
- Ascent Vehicle Integrity
- Booster Separation
- ESM Fairing Jettison
- Nominal LAS Jettison
- LVSA-Core Stage/ICPS Separation

Core Stage Imagery Data Flow:

Critical Events will stream at least one view live



Indicates camera

Space Launch System (SLS) Imagery System

- Organizational Structure
  - Mechanical Design and Manufacturing are critical interfacing organizations
    - Must properly understand design and tolerances of the optical system
    - Mechanical
      - Strength of material
      - Fracture control
    - Optical
      - Jitter dampening
      - Off gassing over the flight envelope thermal and pressure environments
      - Optical clarity of windows
  - Avionics and Software interfaces are also critical
    - Vehicle commands
    - Vehicle electrical power
    - Data telemetry flow
  - Operations interfaces
    - Data routing to the control center
  - Imaging team interfaces
    - Primary customer
  - Manufacturing schedules are an important driver in having the optical system ready for integration onto the vehicle

Space Launch System (SLS) Imagery System

- Policy and Law
  - Imagery system is a support to the launch vehicle
  - National Space Policy
  - NEPA
    - Affects cleaning agents and materials selection
  - Planetary Protection
    - Does not apply since SLS core stage does not achieve orbit

Summary

- System Engineering Framework applies well to Photonic Systems
  - Mission Context
    - Establishes mission environment based on mission type and launch vehicle
  - Optical System Physics
    - Optical Transfer Function (OTF)
  - Organizational Structure
    - Must interface with the other disciplines for the launch vehicle or spacecraft bus
    - Do the optics define the mission or support the mission?
  - Policy and Law
    - Various laws apply depending on the Mission Context
    - EPA regulations constrain available chemicals and materials
- SLS imagery system
  - Mission Context defines key design parameters
  - Optical System Physics
    - Jitter control
    - Data Flow
  - Organizational Relationships
    - Mechanical Design, Manufacturing, Avionics, Software, Operations
  - Policy and Law
    - Primarily NEPA