Astronomical Research Drone (ARD)

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EN.645.800 Systems Engineering Capstone Project
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ARD – Presentation Outline

- Student Biography
- Intro & Need

- Requirements
- ConOps
- Functional Concept
- Physical Concept
- Trade Study

- Risk Management
- Test Plan
- System Specification

- Summary & Next Steps
- Lessons Learned
- Recommendations

Student Biography

- Work
  - Current:
    - Paragon Space Development Corporation - Sr. Systems Engineer
  - Past:
    - World View - Sr. Systems Engineer
    - LSST - Verification Systems Engineer (picture of LSST)
    - Gemini Observatory - Systems Engineer

- Education:
  - BU, Planetary and Space Sciences 2004
  - SDSU, Masters of Science in Astronomy 2007
  - JHU, Masters of Science in Systems Engineering 2019

- Personal
  - Married 2 children
  - Lived in:
    - Hawaii (2007-09) -> Chile/Hawaii (2009-17) -> Tucson (2017-18) -> Chile (2019) -> Tucson (2020)
    - (Somehow still married after all that)

ARD Introduction & Need

(ARD-DOC-001: Project Proposal)

- Introduction: Astronomical Research Drone
  - Drone tech matured and CoTS available
  - Telescope/Camera tech matured and lighter-weight
  - ARD = Integration of Drone, Telescope, Camera

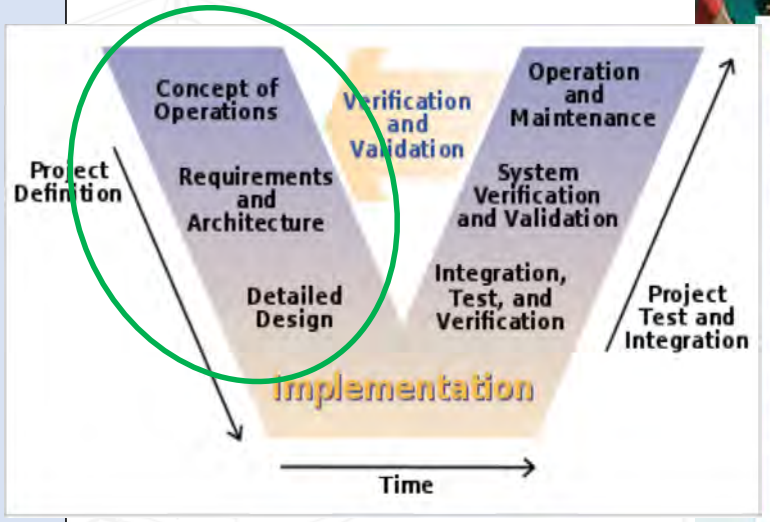
- Need: Why ARD?
  - Attenuation of UV and IR light at ground level = under-sampled regime in Astronomy!
  - SOFIA & Space Telescopes
    - Costly
    - Slow (JWST)
    - Limited science time

ARD fills a gap by providing easier access to UV & IR astronomy

ARD Requirements – Process & User Needs

(ARD-DOC-002: RAR)

- **Activity Description**:
  - **Input**: Concept/Gap/Need
  - **Output**: KPPs, User Needs captured & translated into Technical Requirements
- **Process**:
  - ID Stakeholders
  - Tailor Stakeholder Material
  - Conduct Interviews
  - Define User Needs
  - Define KPPs
  - Draft Initial Context Diagram
  - Draft ConOps & OV-1
  - Initial Set of ARD Requirements



ARD Requirements – User Needs to KPPs

(ARD-DOC-002: RAR)

User Need UID	User Need Title
ARD-NED-001	Extended Objects
ARD-NED-002	ARD Limiting Magnitude - Visible
ARD-NED-003	IR Spectroscopy
ARD-NED-004	UV Spectroscopy
ARD-NED-005	Visible Imaging
ARD-NED-006	Operations and Maintenance Ease
ARD-NED-007	Competition
ARD-NED-008	Flight Altitude
ARD-NED-009	Minimum Observation Time
ARD-NED-010	Level of Science Automation
ARD-NED-011	Minimum Flight Time
ARD-NED-012	Safety for Personnel
ARD-NED-013	Control & "Fun Factor"
ARD-NED-014	ARD Self-Protection

Stakeholders

KPP UID	KPP Title
ARD-KPP-001	Limiting Magnitude – UV
ARD-KPP-002	Observation in IR
ARD-KPP-003	Limiting Magnitude - Visible
ARD-KPP-004	Field of View – Visible
ARD-KPP-005	Spectra & Imaging
ARD-KPP-006	Minimum Flight Time
ARD-KPP-007	Minimum Flight Altitude
ARD-KPP-008	Minimum Max Exposure Time

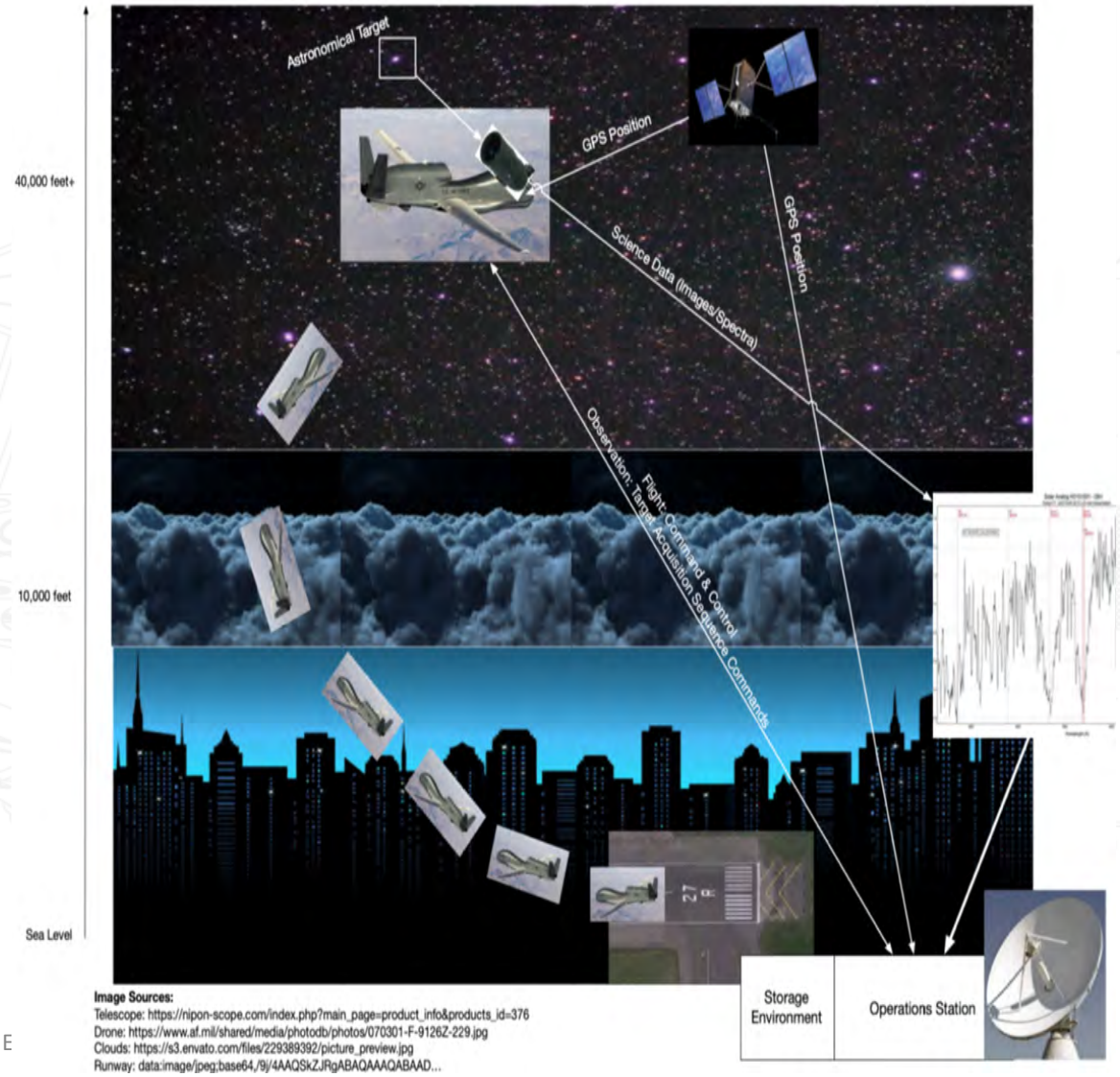
Example, ARD-KPP-001: "The ARD system shall deliver throughput of 80% QE at the Be UV feature at 313nm, with a goal of reaching Boron at 250nm."

ARD – OV-1

(ARD-DOC-002: RAR)

- **Activity Description**:
  - **Inputs**: Concept, User Needs, Stakeholder Feedback
  - **Outputs**: Graphical Representation of Operations

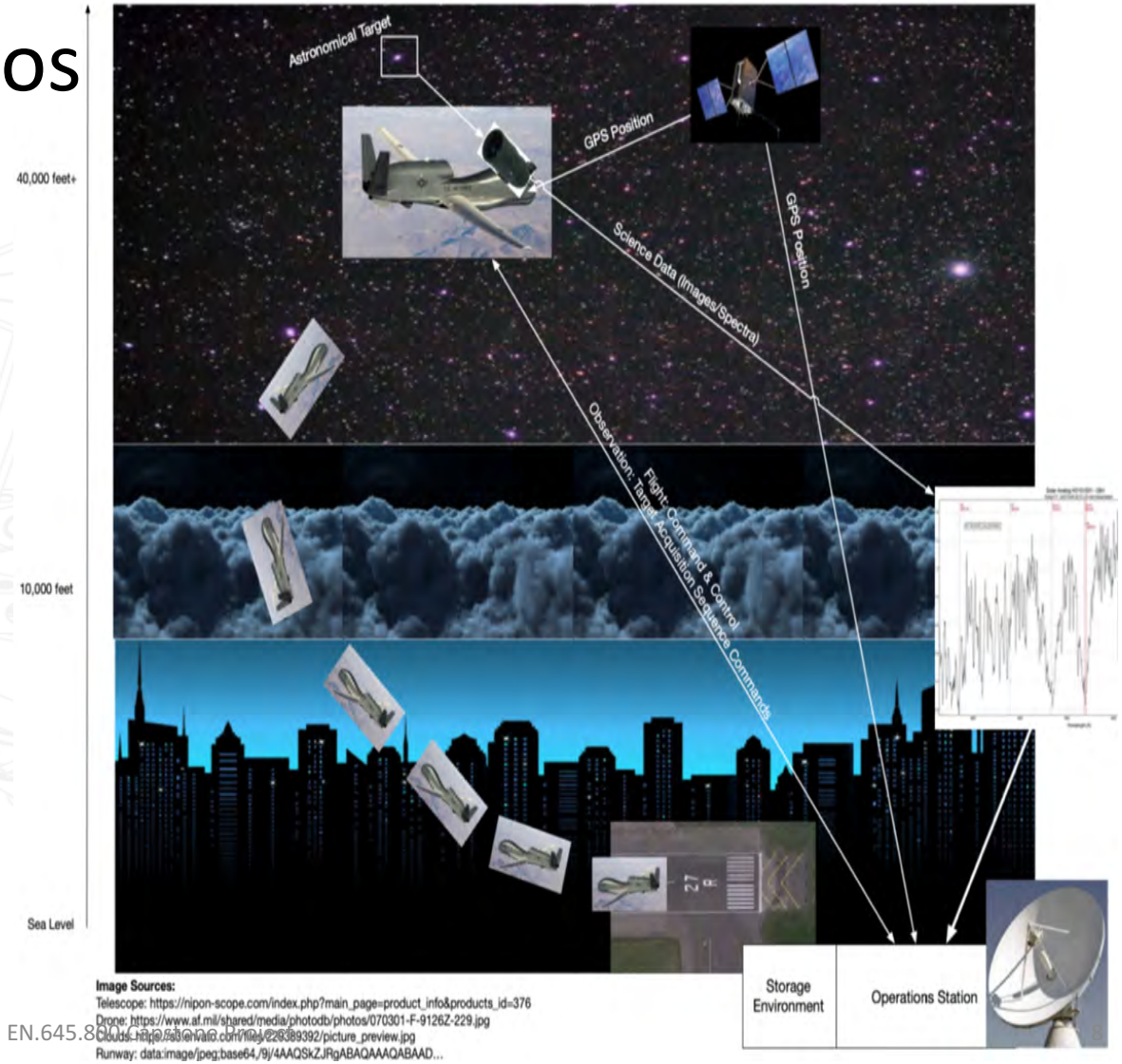
- **OV-1 Description:**
  - ARD launches/takes off
  - Ascends to Observation Altitude
  - Deploys Scientific Payload
  - Acquires Astronomical Target
  - Begins Image/Spectra
  - Relays Data to Control Station
  - Returns to Base (not shown)



ARD ConOps – Scenarios

(ARD-DOC-002: RAR)

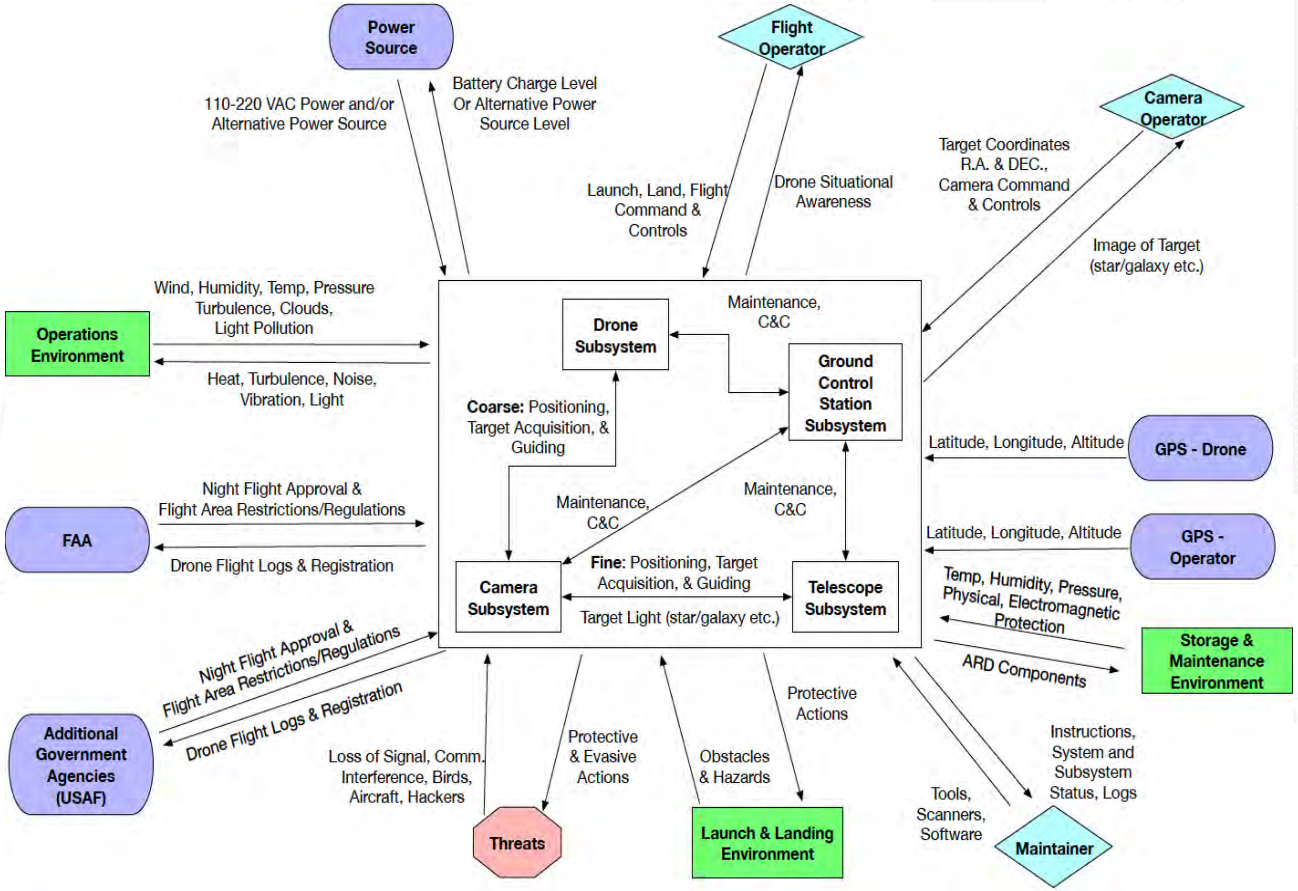
- **Identified Scenarios**
  - Scenario 1: Pre-Flight Target Selection
  - Scenario 2: From Launch to Land
  - **Scenario 3: Target Acquisition to Science**
  - Scenario 4: Physical Prep for Subsequent Flight



ARD Functional Concept – Context Diagram

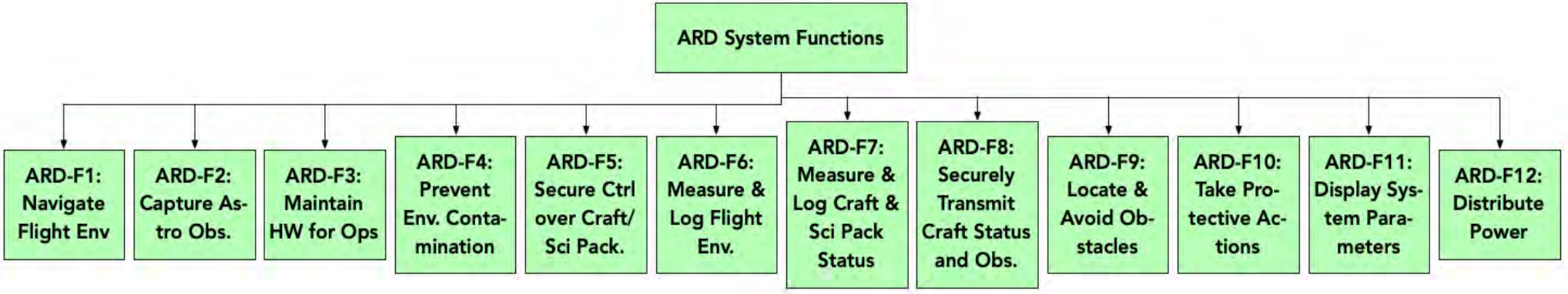
(ARD-DOC-003: FAR)

- **Activity Description:**
  - **Inputs**: Initial Context Diagram, Stakeholder Input, Research & Expertise
  - **Outputs**: Updated Context Diagram
- **Process**:
  - Pull from Stakeholder Questionnaire, Feedback, ConOps, OV-1 & Requirements
  - Wear "Perspectives Hat"
  - Focus on External Entities' interactions with ARD
  - Describe high-level interactions between ARD Subsystems



ARD Functional Concept – Function Tree – Lvl 0-1

(ARD-DOC-003: FAR)

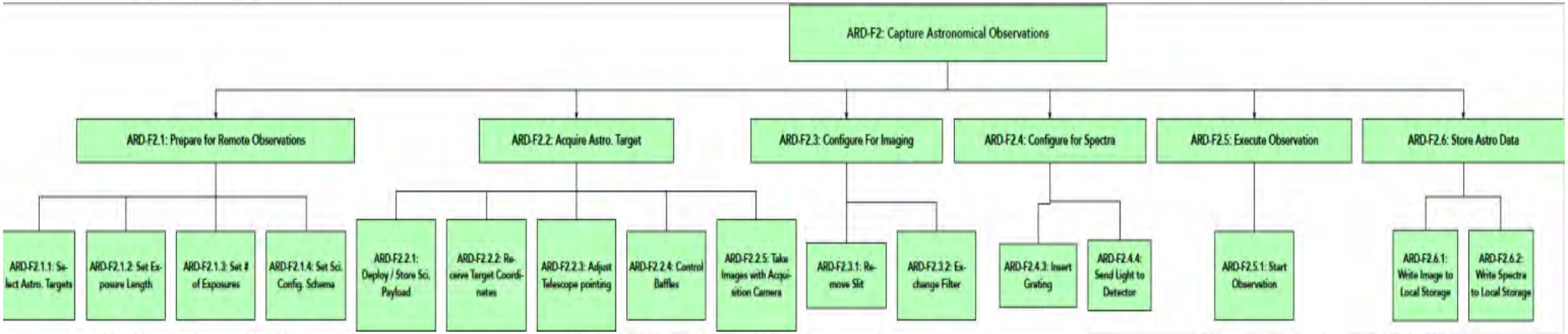


- **Activity Description:**
  - **Inputs**: Requirements, Scenarios, Stakeholders
  - **Outputs**: Allocated Set of Functions & Requirements

- **Process**:
  - Review requirements, translate into high-level functions, using **verb** + [object]
    - Example: ARD-F2: **Capture** + [Astronomical Observations]
  - All Level 1 Functions decomposed to Level 2
  - Key Functions ARD-F2 and ARD-F11 decomposed to Level 3

ARD Functional Tree – ARD-F2: Capture Astronomical Observations – Lvl 1-3

(ARD-DOC-003: FAR)



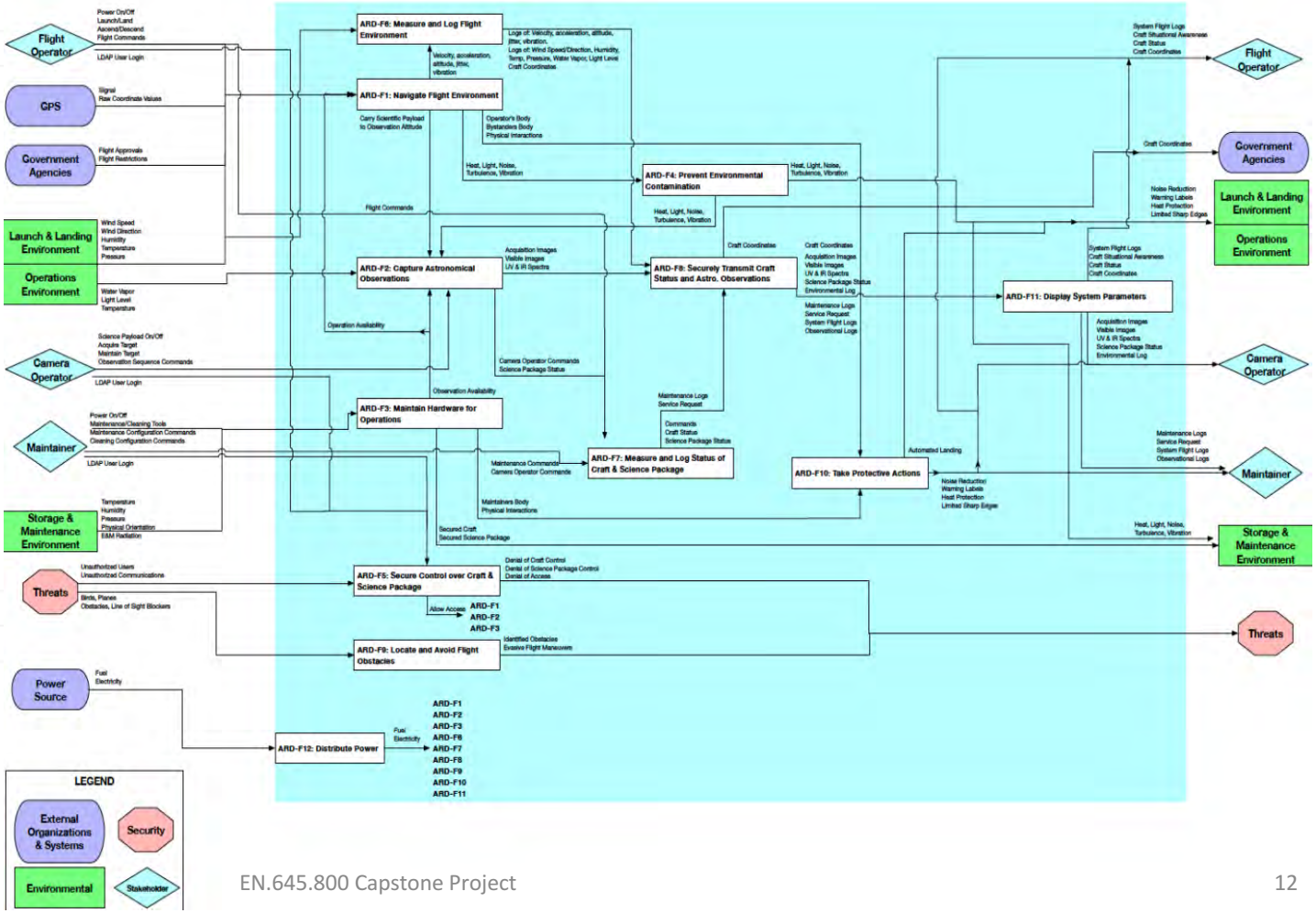
- **Activity Description:**
  - **Inputs**: Lvl 1,2 Functions, Requirements, Scenarios, Stakeholders
  - **Outputs**: Decomposed & Allocated set of Level 2,3 Functions

- **Process**:
  - Review requirements and functions, decompose into detailed functions
  - **Example:**
    ARD-F2: Capture Astronomical Observations
    ->ARD-F2.1: Prepare for Remote Observations
    ->ARD-F2.1.1: Select Astronomical Targets
    ->ARD-F2.1.2: Set Exposure Length
    ->…

ARD Functional Concept – Top Level FBD

(ARD-DOC-003: FAR)

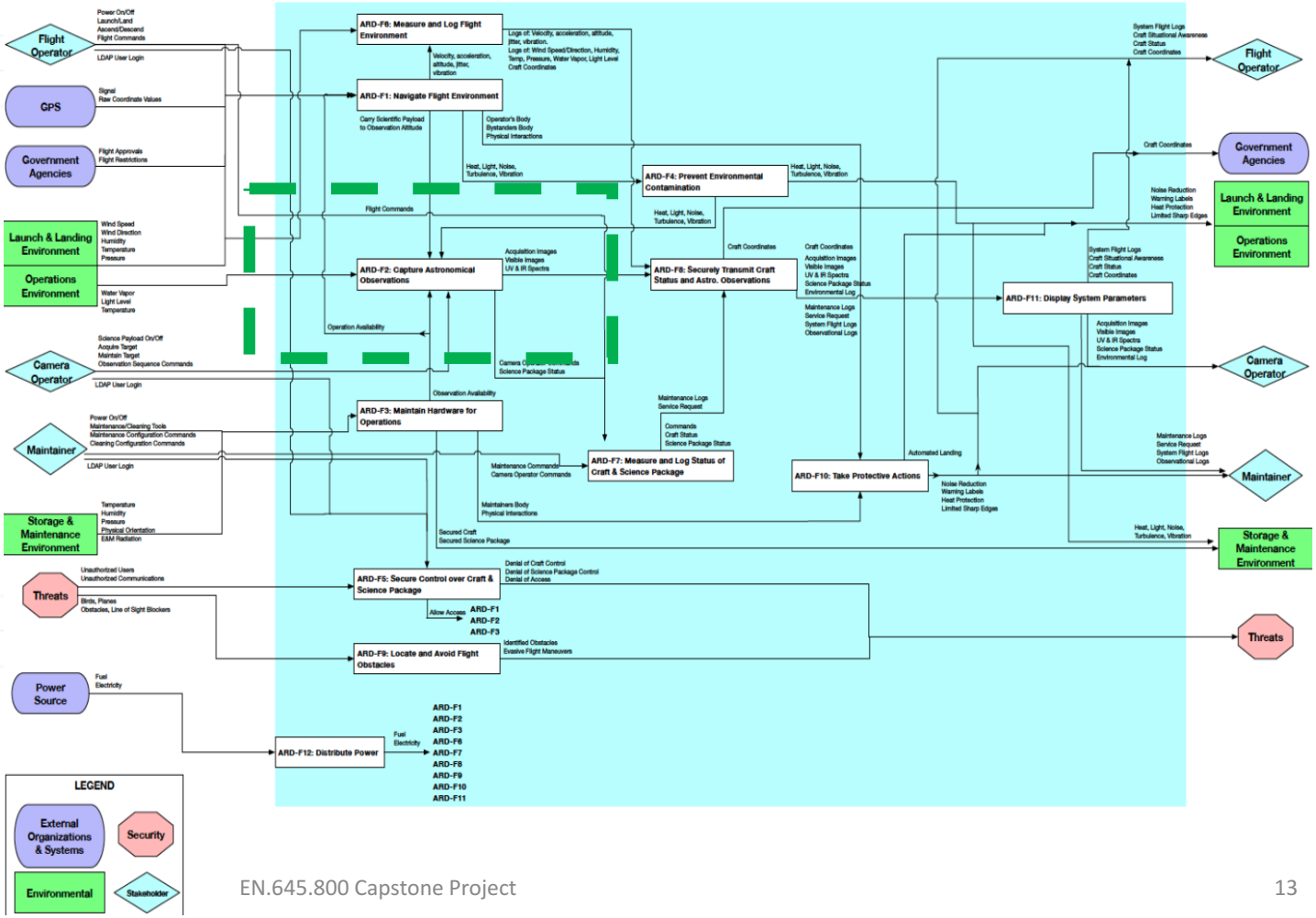
- **Activity Description**:
  - **Inputs**: Context Diagram, Interactions, and Functions
  - **Outputs**: FBD showing interactions between external entities and internal functions
- **Process**:
  - Context Diagram Inputs and Outputs
  - Allocate to ARD functions
  - ID what is passed between each function (not how)
  - Trace back to Context Diagram and Requirements



ARD Functional Concept – Top Level FBD

(ARD-DOC-003: FAR)

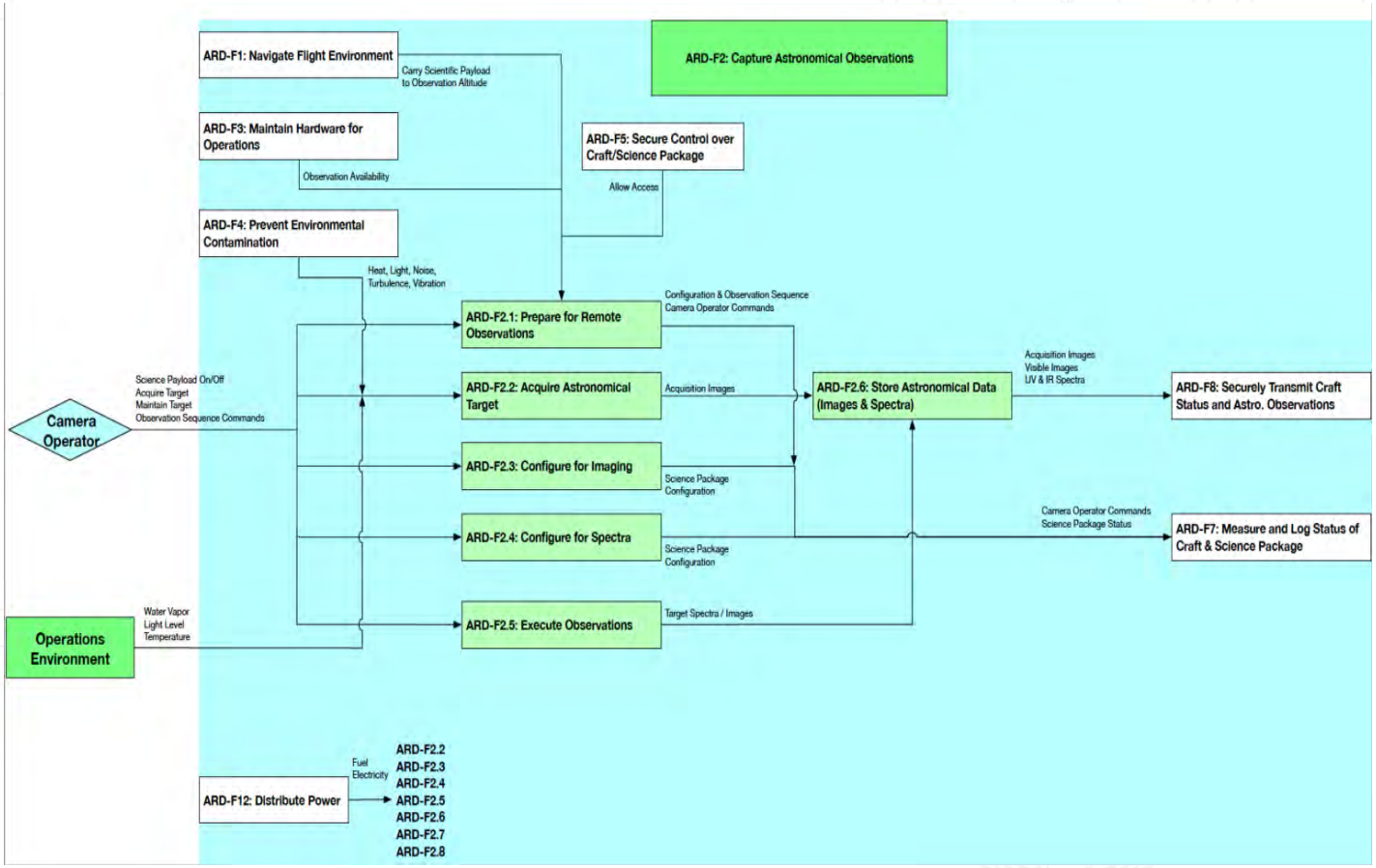
- **Activity Description**:
  - **Inputs**: Context Diagram, Interactions, and Functions
  - **Outputs**: FBD showing interactions between external entities and between functions
- **Process**:
  - Context Diagram inputs and outputs
  - Allocated to ARD functions
  - What is passed between each function (not how)
  - Traceability back to context diagram and requirements



ARD Functional Concept – ARD-F2.0: Capture Astronomical Obs.

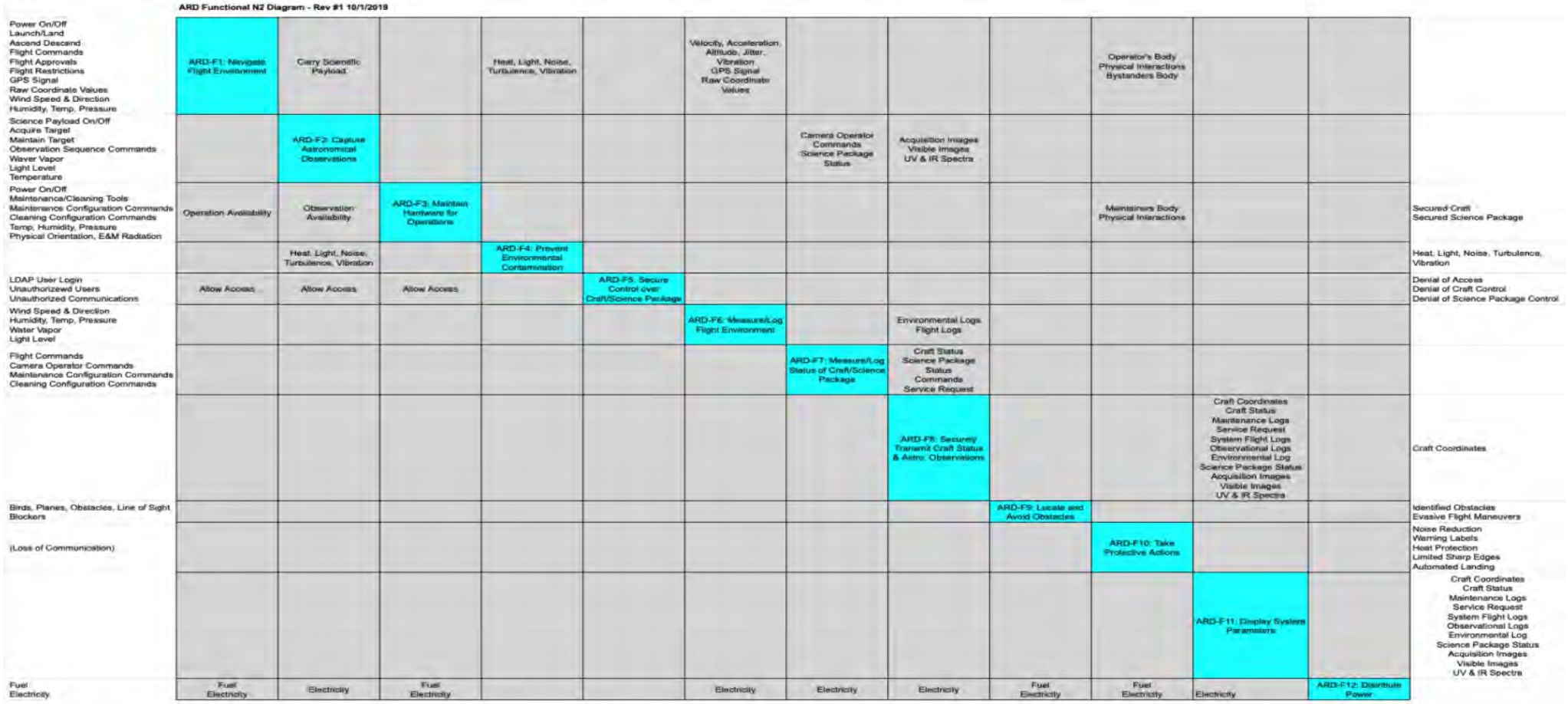
(ARD-DOC-003: FAR)

- **Activity Description**:
  - **Inputs**: ARD-F2 Function, External entities and defined interactions
  - **Outputs**: Decomposed ARD-F2.0 FBD
- **Process**:
  - Decompose F2 into its constitute functions
  - Reuse same external entities
  - Allocate external inputs to correct functions
  - Review for traceability and consistency



ARD Functional Concept – Top Level Functional N2

(ARD-DOC-003: FAR)



ARD Functional Concept – Functions to Reqs. Summary

(ARD-DOC-003: FAR)

- **Activity Description**:
  - **Inputs**: Functions & Requirements
  - **Outputs**: Allocated Functions to Requirements
- **Process**:
  - ID Functions with **NO** Requirements
  - ID Functions with **##** Requirements
  - ID Requirements with **NO** Functions
  - ID Requirements with **##** Functions

REQ ID (ARD-REQ-###)	Function ID	Function Title
030; 036; 038; 040; 052; 092;	**ARD-F1**	**Navigate Flight Environment**
015;	ARD-F1.1	Calculate 3-D Position Space
001; 097; 098; 137; 142;	ARD-F1.2	Launch & Land Safely
057; 058; 059; 099;	ARD-F1.3	Ascend/Descend to Flight Altitude
001; 081; 096;	ARD-F1.4	Receive Remote Flight Commands
004;	ARD-F1.5	Execute Remote Flight Commands
094; 095; 108;	ARD-F1.6	Execute Pre-defined Flight Path
093; 099; 122, 130;	ARD-F1.7	Carry Scientific Payload
052; 059; 067; 068;	**ARD-F2**	**Capture Astronomical Observations**
078; 079; 080;	ARD-F2.1	Prepare for Remote Observations
008; 078; 079; 080;	ARD-F2.1.1	Select Astronomical Targets
009; 132;	ARD-F2.1.2	Select Exposure Length
010;	ARD-F2.1.3	Set Number of Exposures
103;	ARD-F2.1.4	Set Science Configuration Schema
047; 048; 066; 072;	ARD-F2.2	Acquire Astronomical Target
113; 125;	ARD-F2.2.1	Deploy/Store Scientific Payload
006;	ARD-F2.2.2	Receive Target Coordinates (RA & DEC)
007; 124;	ARD-F2.2.3	Adjust Telescope Pointing
101;	ARD-F2.2.4	Control Baffles (Extended/Retracted)
062; 133;	ARD-F2.2.5	Take Image with Acquisition Camera
007; 100;	ARD-F2.2.6	Receive Target Offsets
007; 100; 128;	ARD-F2.2.7	Apply Target Offsets
100; 109; 110	ARD-F2.2.8	Calculate Position/Focus Offsets
060; 109;110	ARD-F2.2.9	Apply Position/Focus Offsets
062;	ARD-F2.3	Configure for Imaging
114; 136;	ARD-F2.3.1	Remove Slit
114; 135;	ARD-F2.3.2	Exchange Filter
114;	ARD-F2.3.3	Remove Grating

REQ ID (ARD-REQ-###)	Function ID	Function Title
064;	ARD-F2.3.4	Send Light to Detector
060; 062;	ARD-F2.4	Configure for Spectra
063; 065; 114; 135;	ARD-F2.4.1	Exchange Filter
063; 065; 114; 136;	ARD-F2.4.2	Insert Slit
063; 065; 114;	ARD-F2.4.3	Insert Grating
069;	ARD-F2.4.4	Send Light to Detector
011; 062; 134	ARD-F2.5	Execute Observations
077; 115;	ARD-F2.5.1	Start Observation
115;	ARD-F2.5.2	End/Readout Observation
115;	ARD-F2.5.3	Pause Observation
116;	ARD-F2.5.4	Add/Remove Observation
009; 077;	ARD-F2.5.5	Adjust Exposure Time
089;	ARD-F2.6	Store Astronomical Data (Images & Spectra)
090;	ARD-F2.6.1	Write Images to Local Storage
090;	ARD-F2.6.2	Write Spectra to Local Storage
052; 056; 073; 074; 121; 129; 145	**ARD-F3**	**Maintain Hardware for Operations**
053; 061; 076; 106; 123;	ARD-F3.1	Receive Maintenance
053; 105; 123; 131;	ARD-F3.2	Receive Cleaning
075;	ARD-F3.3	Receive Software Maintenance and Updates
017;	**ARD-F4**	**Prevent Environmental Contamination**
021; 042; 125; 127;	ARD-F4.1	Shield Science Package from Environment
037; 041; 044; 126;	ARD-F4.2	Shield Science Package from Light Sources
032; 033; 034; 035	ARD-F4.3	Operate System in Extreme Environment
018; 019; 020;	ARD-F4.4	Store System Safely
045;	**ARD-F5**	**Secure Control over Craft/Science Package**
031; 102;	ARD-F5.1	Allow Authorized Users
024;	ARD-F5.2	Reject Unauthorized Users
025;	ARD-F5.3	Reject Unauthorized Communication

ARD Functional Concept – Functions to Reqs. Summary

(ARD-DOC-003: FAR)

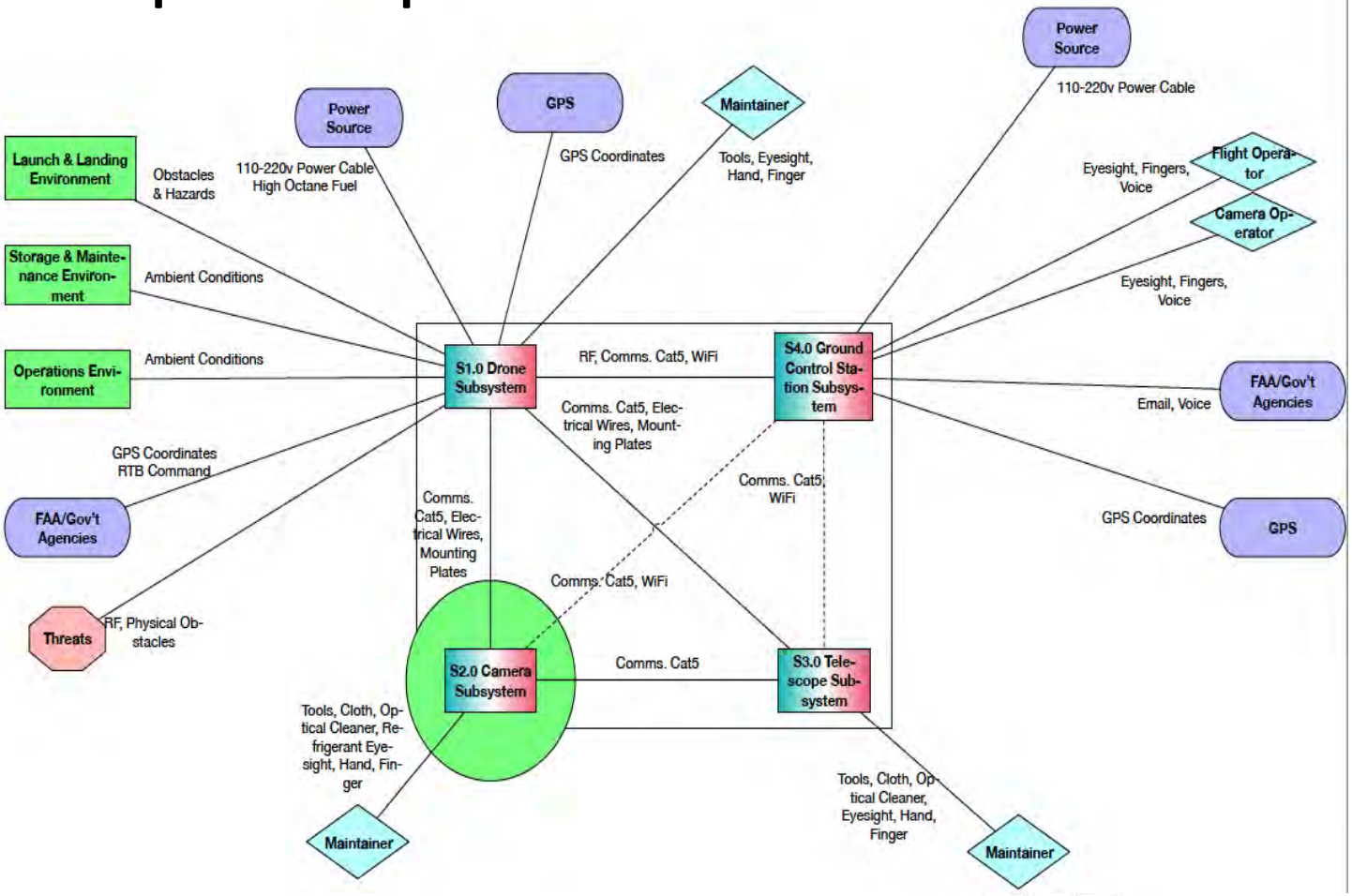
REQ ID (ARD-REQ-###)	Function ID	Function Title
049; 140;	**ARD-F6**	**Measure and Log Flight Environment**
039; 049;	ARD-F6.1	Measure Environmental Variables
039; 049;	ARD-F6.2	Log Environmental Variables
049;	ARD-F6.3	Measure Flight Variables
049;	ARD-F6.4	Log Flight Variables
054;	**ARD-F7**	**Measure and Log Craft/Science Package Status**
117;	ARD-F7.1	Measure Component Positions
117;	ARD-F7.2	Measure Component States
112;	ARD-F7.3	Measure Power Consumption
117;	ARD-F7.4	Log Component Positions
117;	ARD-F7.5	Log Component States
028; 051;	ARD-F7.6	Log Component Failures (Faults)
112;	ARD-F7.7	Log Power Consumption
118;	ARD-F7.8	Log Flight Operator Commands
118;	ARD-F7.9	Log Camera Operator Commands
118;	ARD-F7.10	Log Maintainer Commands
045; 054; 096;	**ARD-F8**	**Securely Transmit Craft Status and Astronomical Observations**
031; 119	ARD-F8.1	Transmit System Position
028; 051	ARD-F8.2	Transmit System Health
050; 111;	ARD-F8.3	Transmit Environmental Conditions
119;	ARD-F8.4	Transmit Science Package Configuration
012; 089;	ARD-F8.5	Transmit Acquisition Image
012; 089;	ARD-F8.6	Transmit Astronomical Data (Images & Spectra)
026; 027;	ARD-F9	Locate and Avoid Flight Obstacles
003; 022; 138;	ARD-F9.1	Identify Obstacles
023; 139;	ARD-F9.2	Avoid Obstacles

REQ ID (ARD-REQ-###)	Function ID	Function Title
091; 094;	**ARD-F10**	**Take Protective Actions**
043; 104; 105;	ARD-F10.1	Protect People from Hazards
029;	ARD-F10.2	Protect System from Communication Loss
119; 141;	**ARD-F11**	**Display System Parameters**
119; 143;	ARD-F11.1	Display for Flight Operator
002;	ARD-F11.1.1	Display Drone Position
118;	ARD-F11.1.2	Display Flight System Configuration
119;	ARD-F11.1.3	Display Science Package Configuration
055;	ARD-F11.1.4	Display System Health & Faults
003;	ARD-F11.1.5	Display Environmental Variables
107; 108;	ARD-F11.1.6	Display Flight Variables
083; 084; 085; 086; 087; 088;	ARD-F11.1.7	Display Power Levels
119; 144;	ARD-F11.2	Display for Camera Operator
119;	ARD-F11.2.1	Display Science Package Configuration
013; 014;	ARD-F11.2.2	Display Visible Image
013; 014;	ARD-F11.2.3	Display UV Spectra
013; 014;	ARD-F11.2.4	Display IR Spectra
005;	ARD-F11.2.5	Display Target Position
055; 119;	ARD-F11.3	Display for Maintainer
118;	ARD-F11.3.1	Display Flight System Configuration
055;	ARD-F11.3.2	Display System Health & Faults
054;	ARD-F11.3.3	Display System Logs
083; 084; 085; 086; 087; 088;	ARD-F11.3.5	Display Power Levels
046;	**ARD-F12**	**Distribute Power**
082;	ARD-F12.1	Receive Power
120;	ARD-F12.2	Distribute Power to Flight System
120;	ARD-F12.3	Distribute Power to Science Package

ARD Physical Concept – Top Level PBD

(ARD-DOC-005: CDR)

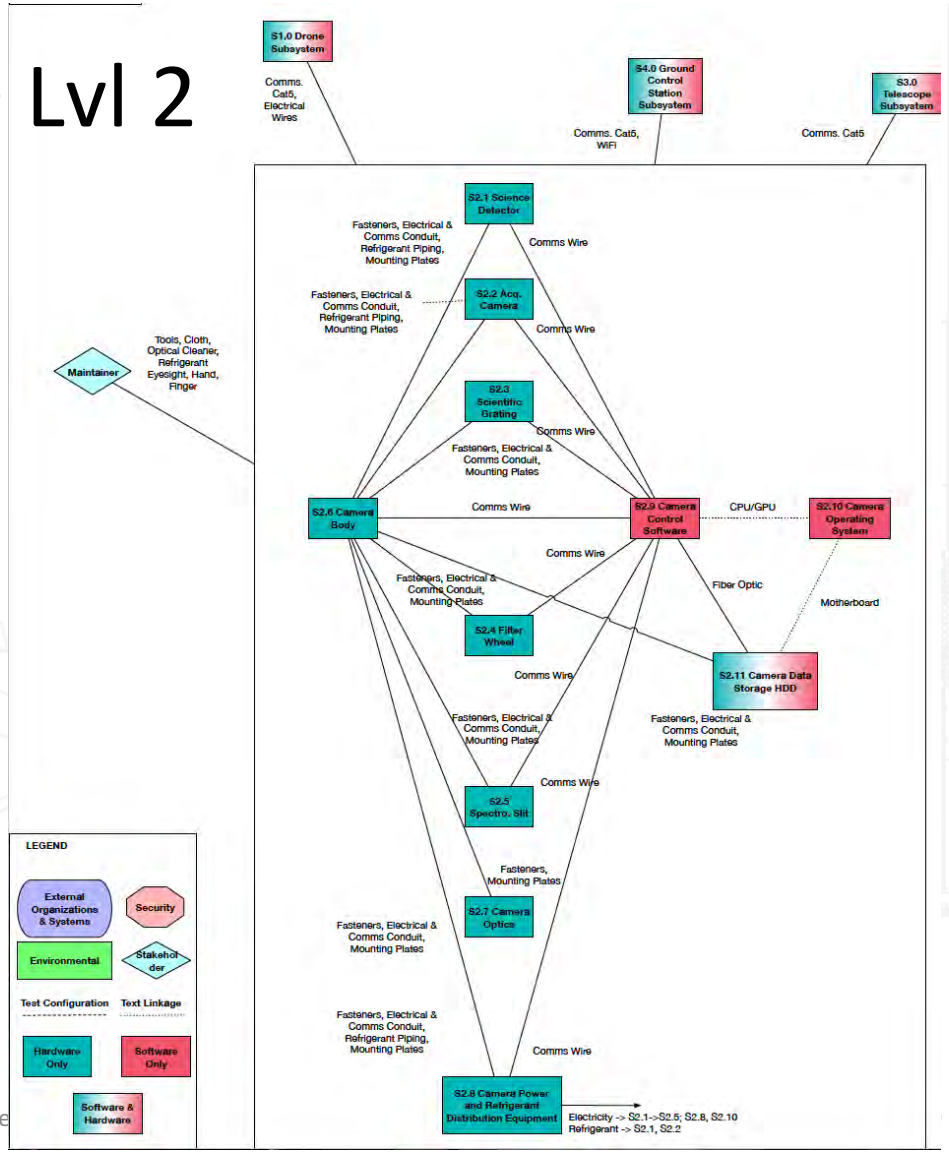
- **Activity Description**:
  - **Inputs**: Context Diagram, Requirements, Stakeholders, Research
  - **Outputs**: Physical interfaces & interactions between external Entities and internal Subsystems
- **Process**:
  - Convert Context Diagram interactions to physical implementations
  - Using sources above
  - Decompose each subsystem



ARD Physical Concept – PBD Lvl 2

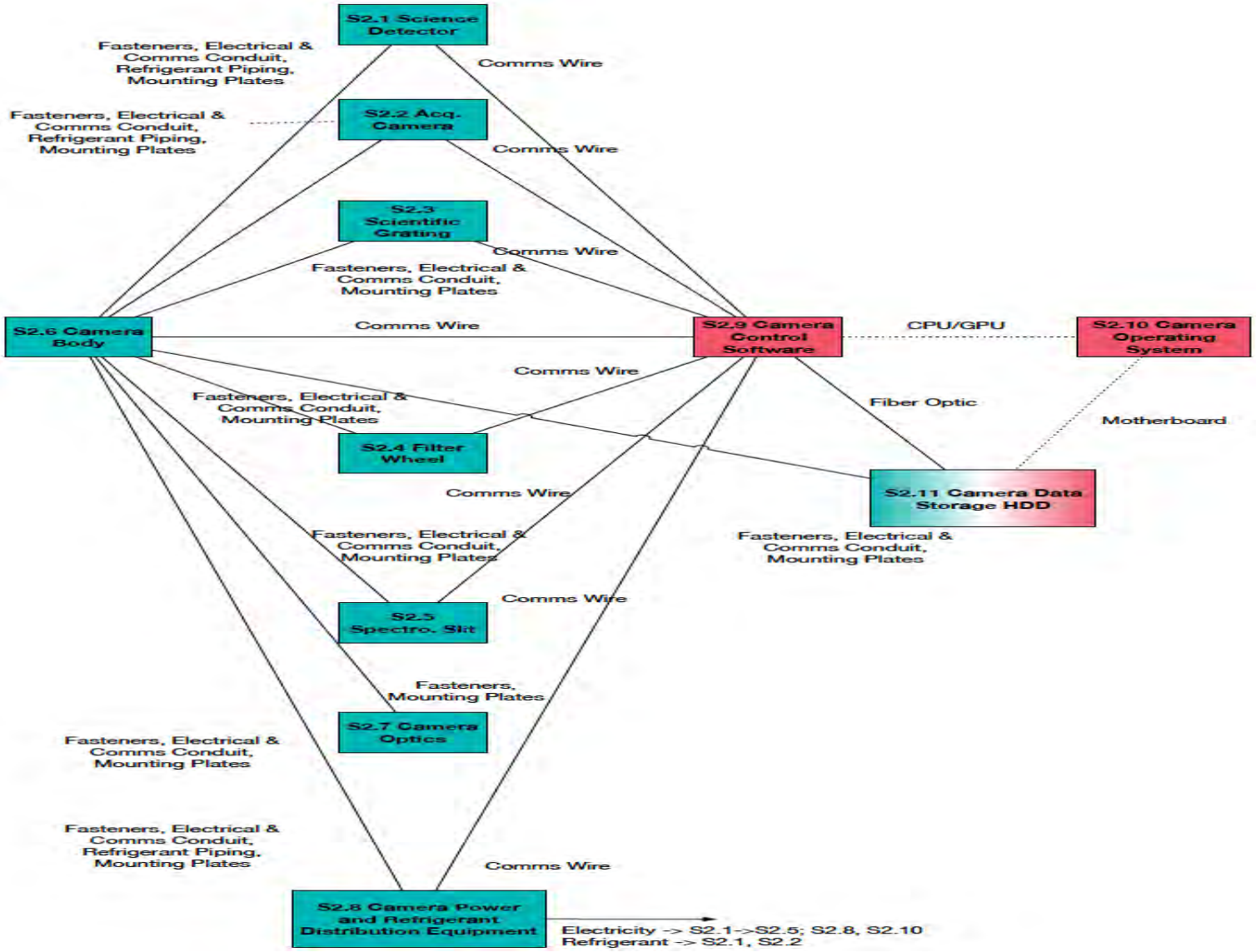
(ARD-DOC-005: CDR)

- **Activity Description:**
  - **Inputs**: PBD Lvl 1
  - **Outputs**: Level 2 Physical Interfaces
- **Process**:
  - Decompose subsystem into its largest components
  - Show how each component interfaces
  - Identify HW, SW, mix



ARD Physical Concept – PBD Lvl 2

(ARD-DOC-005: CDR)



ARD Physical Concept – Physical Interface Description

(ARD-DOC-005: CDR)

Interface ID	Interface Name	Description	Components Connected	Mapping to: Function or Functional Interaction Performed	Implementation Type: Electrical, Mechanical, Air, etc.	What is being passed on the interface
ARD_S1_INT_1	**Fasteners_1**	**Secure Engines to the Drone Body**	**S1.1, S1.2**	**ARD-F1.3 Ascend/Descent to Flight Altitude**	**Mechanical**	**Force**
ARD_S1_INT_2	Conduit_1	Provide wiring access to Engines	S1.1, S1.2	ARD-F12.2 Distribute Power to Flight System	Mechanical	Wires
ARD_S1_INT_3	**FuelPiping_1**	**Provide fuel access to engines**	**S1.1, S1.2**	**ARD-F12.2 Distribute Power to Flight System**	**Mechanical**	**Fuel**
ARD_S1_INT_4	Mounting_1	Attach Engines to Drone Body	S1.1, S1.2	ARD-F1 Navigate Flight Environment	Mechanical	Force
ARD_S1_INT_5	Comms_1	Communications wiring to control Engines	S1.10, S1.2	ARD-F1 Navigate Flight Environment	Electronic	Digital I/O
ARD_S1_INT_6	10GaugeWire_1	Electrical Wiring to power Engine auxiliary systems	S1.9, S1.2	ARD-F12.2 Distribute Power to Flight System	Electrical	AC Voltage
“”	“”	“”	“”	“”	“”	“”

ARD Physical Concept – N2 Diagram – Lvl 1

(ARD-DOC-005: CDR)

- **Activity Description**:
  - **Inputs**: PBD, External Entities, Internal Subsystems & high-level interfaces
  - **Outputs**: N2 Diagram
- **Process**:
  - List all physical interfaces
  - Verify traceability
  - Decompose to level 2
  - Verify consistency and traceability with Lvl2 PBDs (not shown)

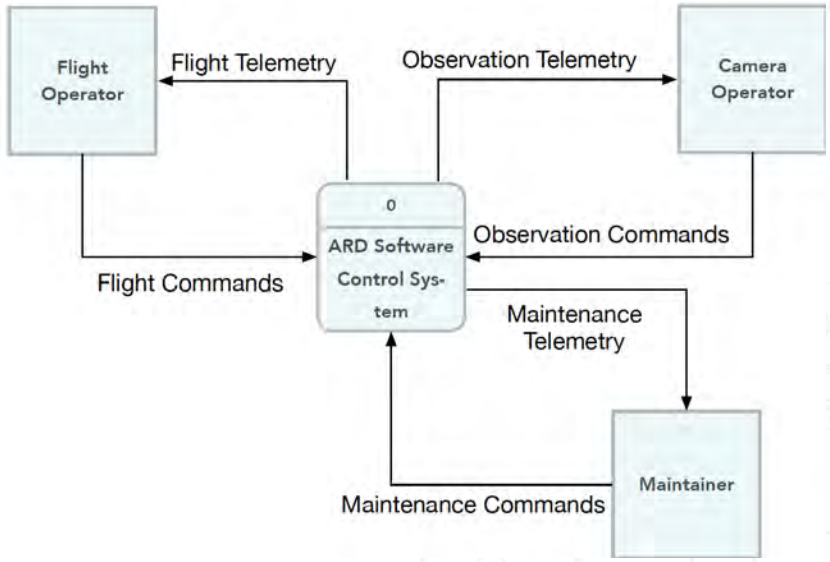
ARD System – Physical N2 Diagram – Level 1

External Entity Inputs				
110-220v Power Cable High Octane Fuel Obstacles & Hazards Ambient Conditions GPS Coordinates RTB Command RF Physical Obstacles Tools, Eyesight, Hand, Finger	**S1.0 Drone Subsystem**	Comms. Cat5, Electrical Wires Mounting Plates	Comms. Cat5, Electrical Wires Mounting Plates	
Tools, Cloth, Optical Cleaner, Refrigerant, Eyesight, Hand, Finger		**S2.0 Camera Subsystem**	Comms. Cat5	
Tools, Cloth, Optical Cleaner, Eyesight, Hand, Finger			**S3.0 Telescope Subsystem**	
110-220v Power Cable Eyesight, Fingers, Voice Email GPS Coordinates	RF, Comms. Cat5, WiFI	Comms. Cat5, WiFI	Comms. Cat5, WiFI	**S4.0 Ground Control Station Subsystem**

ARD Physical Concept – DFD lvl 0

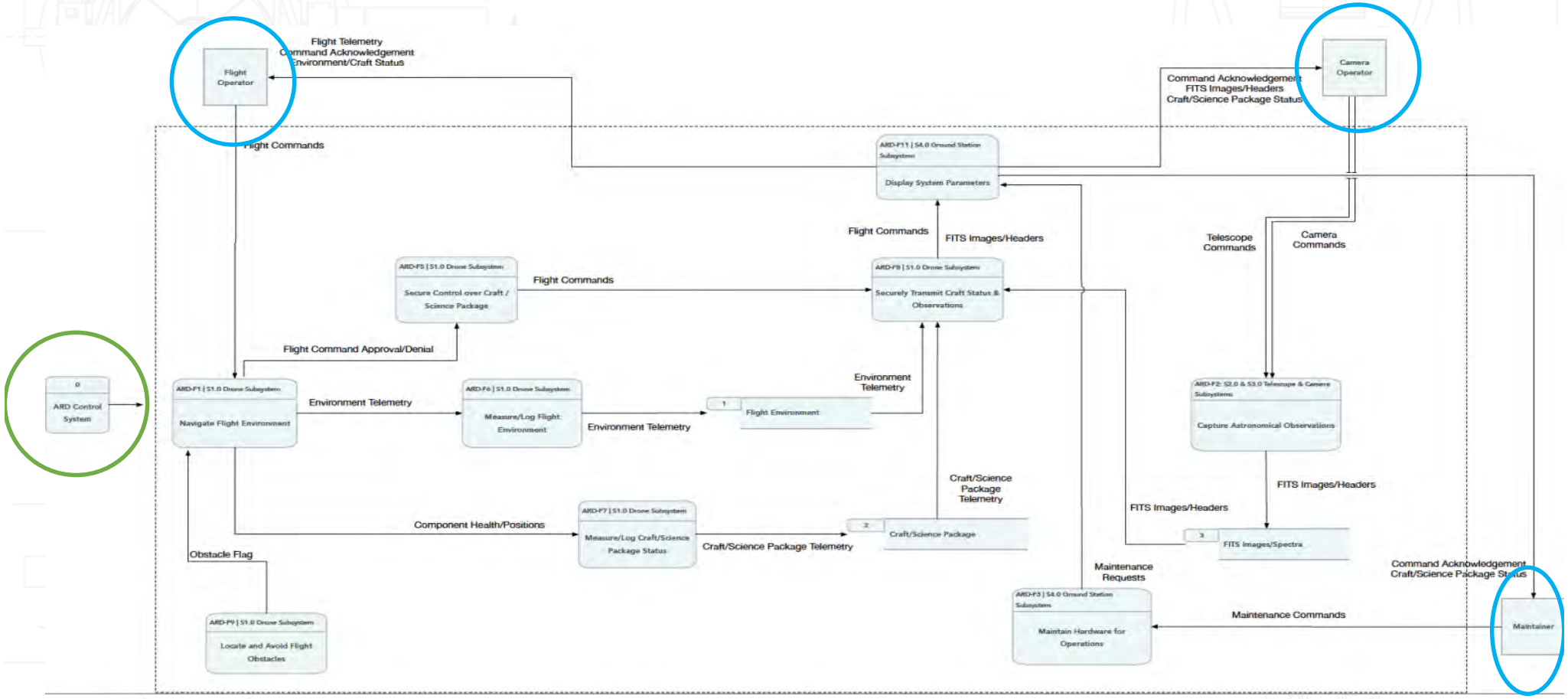
(ARD-DOC-005: CDR)

- **Activity Description**:
  - **Inputs**: External Users, Context Diagram, Scenarios
  - **Outputs**: Depiction of interactions between External Users and the ARD SW Control System
- **Process**:
  - Take Context Diagram and focus on users' interactions
  - Ask: what they are sending in, and what do they need to get out of the ARD SW system?



ARD Physical Concept – DFD lvl 1

(ARD-DOC-005: CDR)



ARD Physical Concept – Data Definition Table

(ARD-DOC-005: CDR)

Field Name	Type	Format	Description	Example(s)
Flight Commands	Text	Text/Integer	Commands on the speed, direction, tilt, altitude etc.	Flt_Alt = 40000 feet; Flt_Spd = 20 mph
Flight Command Approval/Denial	Integer	Binary	If the command is allowed and approved it is a 1, if not it sets a 0.	An erroneous command to fly to an altitude -100 feet would set this value to 0.
Flight Telemetry	Integer	NNNN, unit	Value and unit for each Flight Variable	Altitude = 10,000 feet; Speed = 100 feet / second Direction = 300 degrees
Command Acknowledgement	Integer	Binary	Acknowledged = 1; Not Acknowledge or Unknown = 0 (For flight, telescope/camera, and maintenance commands)	The Flight Operator gives the Land Command. The Craft acknowledges this, and the Flight Operator sees that the command has been received and applied.
Obstacle Flag	Integer	Binary	Obstacle = 0; Clear = 1	If the ARD detects an obstacle it sets the Obstacle Flag = 1 which will then cause it to engage evasive maneuvers.
Env. Telemetry	Integer	NNNN, unit	Value and unit for each Environmental Variable.	Humidity = 85%; Wind Speed = 10 m/s; Temperature = 10 C
Component Health	Integer	Binary	Fault = 0; OK = 1	Motor Controller is in a Fault State, health transitions 1 -> 0
Component Positions	Text	Text	Component Positions can be: In, Out, Idle, Open, Closed, Unknown	Filter Wheel = In; Grating = Out; Telescope Cover = Open
Craft Telemetry	**Integer**	**NNNN**	**Motor Encoder values, set the component position flags, or raw values of low level flight firmware (engine RPMs, battery charge etc.)**	**Engine Gimbals Encoder = 34,300 units**
Science Package Telemetry	Integer	NNNN	Motor Encoder values, used to set the component position flags, for the science payload	Telescope Mount X-direction offset = 158 units; Grating Tilt = 330 units
FITS Images	Integer	NxN Array	Astronomical data (images/spectra) that are written as integers or in floating-point format.	Astronomical Image from ARD Detector with filename IMG_YYYYMMDD_X.fits
FITS Header	**Integer**	**NxN Array**	**Part of the FITS file, that includes telemetry relevant to the observation such as Target Name, Position, Time of Observation, and many other parameters related to the target as well as the Telescope, Camera, Craft. Full FITS Header info needs to be defined with Astronomy Stakeholders.**	**If imaging/spectra of Triangulum Galaxy: ObjDec = Dec +30° 39′ 37″; ObjRA = 1h 33m 50s; ExpTime = 600s**
Telescope Commands	Text	Text/Integer	Commands sent to the Telescope subsystem to adjust position, pointing, deployment, opening the cover etc.	TelCovOpen = Opens telescope cover; TelCovClose = closes telescope cover; ParkTel = Stows the telescope; UnparkTel = unstows the telescope for observations
Camera Commands	Text	Text/Integer	Commands sent to the Camera subsystem for adjusting the camera configuration (slit, grating, filter wheel, exposure duration, number of exposures).	ExpNum = 10; ExpTime = 100s Slit_Park = extracts slit; Slit_Beam = puts slit into the beam
Maint. Commands	Text	Text/Integer	Maintenance Related Commands sent to the ARD, which will put it into Maintenance Configurations.	TelCovMaint = Puts cover into a maintenance position CamShutter = Puts camera shutter into a maintenance position
Maint. Requests	Text	Binary	If a monitored condition is out of tolerance, a request for maintenance will be sent. 1 = OK, 0 = Maintenance needed	TelCovMaintReq = 0 (maintenance needed) CamShutterMaintReq = 1 (all OK)

ARD Physical Concept – Component to Function Tree

Component ID & Name	ARD F-ID
S1.0 - Drone Subsystem	
S1.1 - Drone Body	ARD-F1, ARD-F12
S1.1.1 - Metal Panels	ARD-F1.7,
S1.1.2 - Warning/Peligro Labels	ARD-F10.1
S1.1.3 - Fasteners	
S1.1.4 - Energy/Fuel Receptacle	ARD-F1.1
S1.1.5 - Network Cable Receptacle	
S1.2 - Engine(s)	ARD-F1, ARD-F9.2
S1.2.1 - Propellers	
S1.2.2 - Fuel Piping	
S1.2.3 - Engine Housing	
S1.3 – Gimbals	ARD-F1, ARD-F9.2
S1.3.1 - Flight Gimbals	
S1.3.2 - Landing Gear/Strut Gimbals	
S1.3.3 - Camera Gimbals	
S1.3.4 - Electrical Wiring	
S1.4 - Landing Gear	ARD-F1
S1.4.1 - Rubber Wheels	
S1.4.2 - Actuators	
S1.4.3 – Brakes	
S1.5 - Communications Equipment	ARD-F1
S1.5.1 - GPS Receiver	ARD-F1.1
S1.5.2 - Flight Transponder	
S1.5.3 - Radio Antenna	ARD-F1.4, ARD-F5.1
S1.5.4 - WiFi Adaptor	ARD-F1.4
S1.5.5 - Cat5 Cabling	

Component ID & Name	ARD F-ID
S1.6 - Flight Cameras	ARD-F1, ARD-F9.1
S1.6.1 - Visible Wavelength Flight Camera	ARD-F1.3
S1.6.2 - InfraRed Flight Camera	ARD-F1.2
S1.6.3 - Cat5 Cabling	
S1.6.4 - Electrical Wires	
S1.7 - Environmental Sensing Suite	ARD-F1, ARD-F6
S1.7.1 - Anemometer	ARD-F6.1
S1.7.2 - Humidity Sensor	ARD-F6.1
S1.7.3 - One-Wire Temperature Sensors	ARD-F6.1
S1.7.4 - Wave Vapor Monitor	ARD-F6.1
S1.7.5 - Accelerometer	ARD-F6.3
S1.7.6 - Altimeter	ARD-F6.3
S1.7.7 - Barometer	ARD-F6.1
S1.7.8 - Ambient Light Sensor	ARD-F6.1
S1.7.9 - Angular Velocity Sensor	ARD-F6.3
S1.7.10 - Sonar Sensor	ARD-F1.2, ARD-F9.1
S1.7.11 - Cat5 Cabling	ARD-F6.2, ARD-F6.4
S1.7.12 - Electrical Wires	ARD-F6.2, ARD-F6.4
S1.8 - Scientific Payload Storage Envelope	ARD-F1.7, ARD-F4, ARD-F4.4
S1.8.1 - Telescope Interface Plate	
S1.8.2 - Fasteners	
S1.8.3 - Cat5 Cabling	
S1.8.4 - Electrical/Comms Conduit	
S1.8.5 - Electrical Wiring	
S1.8.6 - Sci. Package Cover	ARD-F2.2.1, ARD-F4.1, ARD-F4.2
S1.8.6.1 - Motors	
S1.8.6.2 - Encoders	
S1.8.6.3 - Limit Switches	
S1.8.6.4 - Drivers	

Component ID & Name	ARD F-ID
S1.9 - Energy Distribution Equipment	ARD-F12.3
S1.9.1 - Fuel Piping	ARD-F12.1
S1.9.2 - Electrical Conduit	ARD-F12.2, ARD-F12.3
S1.9.3 - Lithium-Ion Batteries	ARD-F12.2, ARD-F12.3
S1.9.4 - Power Cabling	ARD-F12.1
S1.10 - Done Flight Software	ARD-F7, ARD-F8, ARD-F9
S1.10.1 - Flight Control Software	ARD-F1.3, ARD-F1.6, ARD-F7.1, ARD-F7.2
S1.10.2 - Launch Control Software	ARD-F1.2
S1.10.3 - Land Control Software	ARD-F1.2, ARD-F10.2
S1.10.4 - Sensor Control Software	ARD-F6.2, ARD-F6.4
S1.10.5 - Communications Software	ARD-F1.4, ARD-F2.2.6, ARD-F5.1, ARD-F5.2, ARD-F5.3, ARD-F8.1->F8.6
S1.10.6 - Sci. Package Cover Control Software	ARD-F2.2.1, ARD-F7.1, ARD-F7.2
S1.10.7 - Power Control Software	ARD-F7.7
S1.11 - Drone Operating System	ARD-F1.5
S1.12 Drone Flight Data Storage Harddrive	ARD-F1.6, ARD-F7.4, ARD-F7.5, ARD-F7.6, ARD-F7.7, ARD-F7.8

Component ID & Name	ARD F-ID
S2.8 - Camera Power and Comms Distribution Equipment	ARD-F12.3
S2.8.1 - Electrical Conduit	
S2.8.2 - Network Port	
S2.8.3 - Communications Conduit	
S2.8.4 - Power Cabling	
S2.8.5 - Refrigerant Storage	
S2.8.6 - Refrigerant Distribution Controller	
S2.9 - Camera Control Software	ARD-F2.5
S2.9.1 - Science Detector Control Software	ARD-F2.2.5, ARD-F2.2.8
S2.9.2 - Acquisition Camera Control Software	ARD-F2.2.5, ARD-F2.2.8
S2.9.3 - Grating Control Software	ARD-F2.3, ARD-F2.4
S2.9.4 - Filter Wheel Control Software	ARD-F2.3, ARD-F2.4
S2.9.5 - Slit Control Software	ARD-F2.3, ARD-F2.4
S2.9.6 - Shutter Control Software	ARD-F2.5
S2.9.7 - Refrigerant Distribution Control Software	ARD-F4.3
S2.10 - Camera Operating System	ARD-F2.6.1, ARD-F2.6.2
S2.11 - Camera Data Storage Harddrive	ARD-F2.6, ARD-F7.9

ARD Trade Study – Introduction

(ARD-DOC-004: TSR)

- **Activity Description**:
  - **Inputs**: Requirements, KPPs, ConOps Scenarios, Stakeholder Feedback, Risks
  - **Outputs**: Formal recommendation for system design option
- **Process**:
  - Determine formal trade to conduct
  - Research alternatives
  - Determine selection criteria
  - Weighting
  - Research & Calculate Raw Scores
  - Normalize alternative scores using Utility Functions
  - Calculate Operational Utility & Cost Effectiveness
  - Test for Sensitivity
  - Provide Recommendation

- **Selected Trade: S3.0 Telescope Subsystem**
  - Available CoTS alternatives with largest mirrors
  - High quality optics
  - Compact configurations
  - Fast Slew/Pointing speeds
  - Viable for both Imaging and Spectroscopy
- **Other Formal/Informal Trades Considered**:
  - S1.0 Drone Subsystem – CoTS Option
  - S1.0 Drone Subsystem – Payload Envelope Material
  - S2.0 Camera Subsystem – Detector Substrate
  - S2.0 Camera Subsystem – Coolant Type
  - S2.0 Camera Subsystem – Filter Selection
  - S2.0 Camera Subsystem – Grating Selection
  - S2.0 Camera Subsystem – Software Control Language
  - …

ARD Trade Study – Alternatives & Selection Criteria

(ARD-DOC-004: TSR)

- **Alternative 1**: Meade 16” LX600 ACF Telescope
- **Alternative 2**: Celestron CGX-L Equatorial 1400 HD Telescope
- **Alternative 3**: Officina Stellare Pro RC 600 + Software Bisque Taurus 400 Fork Mount
- **Alternative 4**: ASA 600 Reflecting Telescope + ASA DDM200 Mount

- **Selection Criteria**
  - **Mass Budget (MB) –** ARD-REQ-093
    - Allocation of 400kg for telescope subsystem.
    - Lower = better
  - **Delivered Optical Quality (DOQ) =** ARD-REQ-064; ARD-REQ-067

    *DOQ = 1 - ((Diffraction Limit – Resolution) / Resolution) *100*
    - Higher % = better
  - **Pointing Accuracy (PA)** – ARD-REQ-077; ARD-REQ-047; ARD-REQ-048
    - How accurately mount can slew telescope to target coordinates.
    - Lower PA = better
  - **Guiding Accuracy (GA) –** ARD-REQ-060; ARD-REQ-007; ARD-REQ-110
    - How well target stays in center of the detector field of view.
    - Lower GA = better

ARD Trade Study – Weights, Utility Functions, Raw Scores

(ARD-DOC-004: TSR)

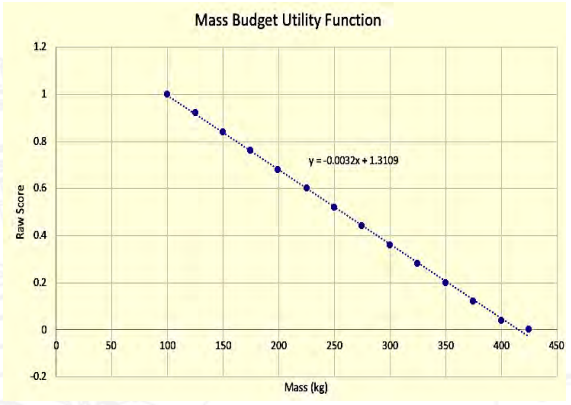
Weights

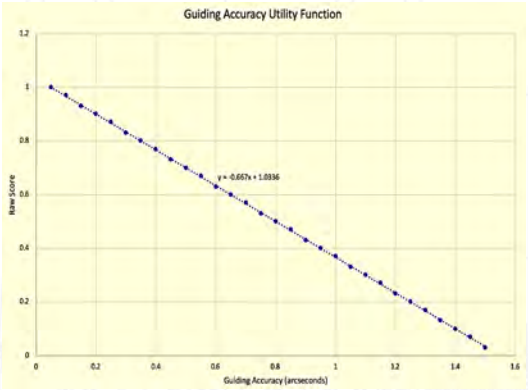
Selection Criteria	Mass Budget	DOQ	PA	GA		Row Value Products	Nth Root	Normalized Weighting Factors
MB	1	3	5	0.2		3.00	1.32	0.26
DOQ	0.33	1	5	1		1.65	1.13	0.22
PA	0.2	0.2	1	0.14		0.006	0.28	0.05
GA	5	1	7	1		35.00	2.43	0.47
							Sum	1.00

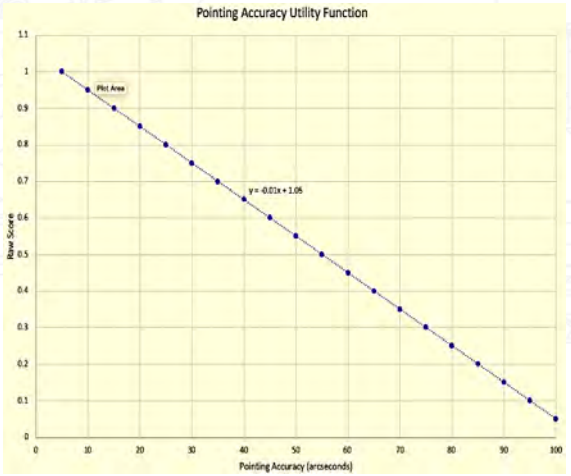
Raw Values

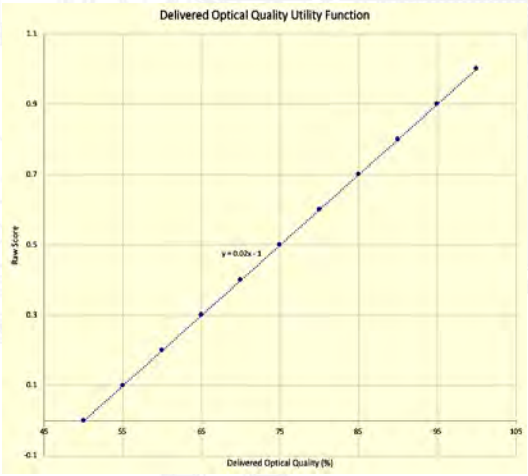
Spec	A1: Meade 16"	A2: Celestron	A3: Officina Stellare Pro	A4: ASA 600
Aperture (cm)	40.64 (16")	35.6 (14")	60.0 (24")	60.0 (24")
Focal Ratio	f/8	f/10	f/8	f/7
Focal Lgt (mm)	3251	3910	4800	4200
Res. (")	0.29	0.33	0.23	0.22
DOQ (%)	82.56	82.18	99.71	95.12
FOV(')	23.1	19.2	15.63	17.9
Max Speed (deg/s)	8	3	3.5	10
PA (")	60	75	10	12
GA (")	1.0	1.5 *	0.20	0.35
Weight (kg)	144.2 kg	44.7 kg	Tel+Mount Total = 275 kg	Tel+Mount Total = 160.6 kg
Tel. Material	Plastic & Aluminum	Plastic & Aluminum	Carbon Graphite Fiber	Aluminum, Carbon Fiber
Mt. Material	Cast-Aluminum	Stainless Steel	6061 Aluminum	Carbon Fiber
Cost ($) Tel + Mount	$16,899.00	$8,699.00	$147,295.00	$65,640

Utility Functions









ARD Trade Study – Scoring the Alternatives

(ARD-DOC-004: TSR)

- **Activity Description**:
  - **Inputs**: Raw scores, weights
  - **Outputs**: Quantitative scoring
  - Recommendation
- **Process**:
  - Plugged in values to calculate Utility Score
  - Calculate Weighted Utility Score
  - Summed for Operational Utility score
  - Divided by Cost (in thousands)
  - Highlighted highest (green) and lowest (orange) scores
  - Provided recommendation <u>based on fact & expertise</u>

Operational Utility and Cost Effectiveness Calculation

			Alternative 1: Meade 16" LX600			Alternative 2: Celestron CGX-L			Alternative 3: OS Pro 600			Alternative 4: ASA 600		
Criteria	Units	Weight	Base Raw Value	Utility Score	Weighted Utility Value	Base Raw Value	Utility Score	Weighted Utility Value	Base Raw Value	Utility Score	Weighted Utility Value	Base Raw Value	Utility Score	Weighted Utility Value
Mass Budget	Kilograms	0.26	144.20	0.85	0.22	44.70	1.00	0.26	275.00	0.43	0.11	160.60	0.80	0.21
Delivered Optical Quality	Arcseconds	0.22	82.56	0.65	0.14	82.18	0.64	0.14	99.71	0.99	0.22	95.12	0.90	0.20
Pointing Accuracy	Arcseconds	0.05	60.00	0.45	0.02	75.00	0.30	0.02	10.00	0.95	0.05	12.00	0.93	0.05
Guiding Accuracy	Arcseconds	0.47	1.00	0.36	0.17	1.50	0.03	0.01	0.20	0.90	0.42	0.35	0.80	0.38
Operational Utility	--			0.56			0.43			0.80			0.83	
Cost	thousand dollars $	--		$16.90			$8.70			$147.30			$65.64	
Cost-Effectiveness		--		32.99			49.43			5.44			12.61	

Rationale for Alternative 4: ASA 600 & ASA DDM200

- **Overall**: Highest in Operational Utility, 3rd in Cost-Effectiveness
- **Mass Budget**: 3rd heaviest. Will require special handling equipment, may impact flight time of Drone Subsystem (future trade required)
- **Delivered Optical Quality**: 2nd best DOQ. Significance: proves it uses high-quality optics and telescope design and <u>can be used for scientific research</u>
- **Pointing Accuracy**: At 12.0", sufficient for stellar object acquisition
- **Guiding Accuracy**: At 0.35", sufficient to keep object centered on slit or detector.
- **Cost**: ASA 600 is the 2nd most expensive of the alternatives considered.

ARD Risk Management

(ARD-DOC-008: RMR)

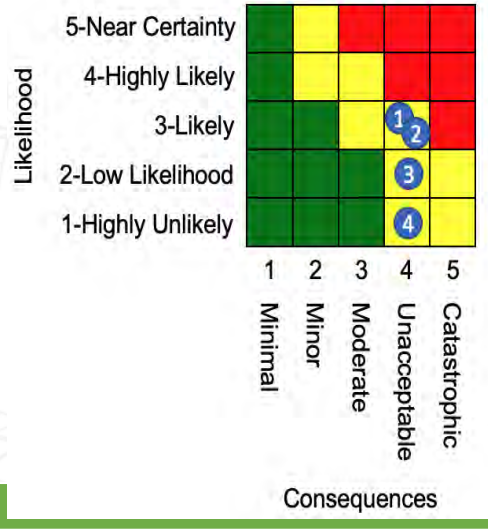
- **Activity Description**:
  - **Inputs**: Stakeholder Feedback, Expertise, Complex Requirements, Scenarios
  - **Outputs**: Technical & Programmatic Risk Register
- **Process**:
  - Formal "**IF** -> **Then**"
  - Evaluate likelihood using Stakeholders, personal experience, research
  - Evaluate impact ""
  - Identify Mitigation Events
  - Track

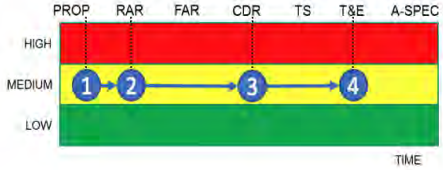
Risk UID	Risk Title	Risk Type	Risk Description	L_ i	C_ i		L_ f	C_ f
ARD-RSK-001	Image Stability	Technical	**IF** the ARD cannot deliver stabilized light to the detector, **THEN** the quality of the astrophotography will be reduced.	3	4		1	4
ARD-RSK-002	Flight Time	Technical	**IF** the ARD cannot stay in flight for the required period of time (4 hours), **THEN** it will reduce the effective sky coverage by limiting the number of objects that can be acquired and imaged to only those that are bright.	3	3		1	3
ARD-RSK-003	Stakeholder Involvement	Programmatic	**IF** the ARD stakeholder interviews and meeting times cannot be secured, **THEN** the ARD will have an incomplete system description, ConOps, and set of requirements.	2	4		4	4
ARD-RSK-004	Image Quality	Technical	**IF** the ARD Drone subsystem's thermal dissipation interferes with the ARD Camera Subsystem Science detector, THEN the ARD subsystem will not be able to image faint objects.	3	4	->	1	4
ARD-RSK-005	Drone SW Integration	Technical	**IF** the standard Drone software cannot be integrated into a common Camera/Drone UI for the user, **THEN** operations may become too complex for customers.	3	4		1	4
ARD-RSK-006	Use of tools	Programmatic	**IF** the ARD development does not use a requirements management tool or MBSE tools, **THEN** it may take too much time to produce diagrams and create, update, and verify traceability between functions, requirements, KPPs, functions, and physical components.	5	3		5	3
ARD-RSK-007	Emergent Behavior	Programmatic	**IF** there is emergent behavior when the ARD subsystems' hardware and software are integrated (Drone, Camera, Telescope) **THEN** it may delay the ARD schedule.	3	4		1	4

ARD Risk Management – ARD-RSK-001: Image Stability

(ARD-DOC-008: RMR)

Risk Title	Image Stability	
RISK UID	ARD-RSK-001	
Description:	**IF** the ARD system cannot deliver stabilized light to the detector, **THEN** the quality of the images and spectra will be reduced.	
Initial Assessment:	Likelihood:	3
	Consequences:	4
	Description of Consequences if realized	The delivered flux to the detector will be reduced, and as a result it will require more time on-sky to achieve a higher Signal-to-Noise Ratio for both imaging and spectra independent of wavelength. In addition, if the image is not stable, the images will be blurred and would not serve for astrophotography or astrometric studies.





Mitigation Plan

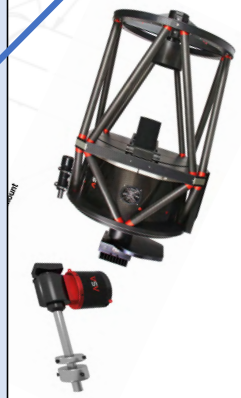
ID	Associated Deliverable	Mitigation Action
ARD-RSK-001-MIT-1	ARD-DOC-001: Project Proposal	Risk initially identified. Mitigation activity was simply to ID and list on the risk register.
ARD-RSK-001-MIT-2	ARD-DOC-002: Requirements Analysis Report	Stakeholder discussion on Image Stabilization and Closed Loop feedback systems.
ARD-RSK-001-MIT-3	ARD-DOC-005: Conceptual Design Report	Design in the Image Stabilization System and the software needed.
ARD-RSK-001-MIT-4	ARD-DOC-006: Test Plan Report	Test of the Image Stabilization in various environmental conditions

ARD Test Plan – Objectives

ARD-DOC-006 (TPR)

Subsystem Under Test: S3.0 Telescope

- **Activity Description**:
  - **Inputs**: KPPs, Risks, Reqs., Interfaces, ConOps
  - **Outputs**: Test Plan that includes Objectives, Environmental Description, Process, Desired Results, Metrology
- **Objectives**:
  - **Early KPP verification**
  - **Risk Mitigation Events**
  - **Early REQ Verification** (062, 063, 069, 072+)
  - **Early Verification** of Environmental Constraints and Safety Hazards
  - **Identify** any missed requirements, technical issues
  - **Characterize System / Train** future operators on system ops, give SW team feedback, update design and procedures, FMEAs



KPP UID	KPP Title
ARD-KPP-001	Limiting Magnitude – UV
ARD-KPP-005	Spectra & Imaging

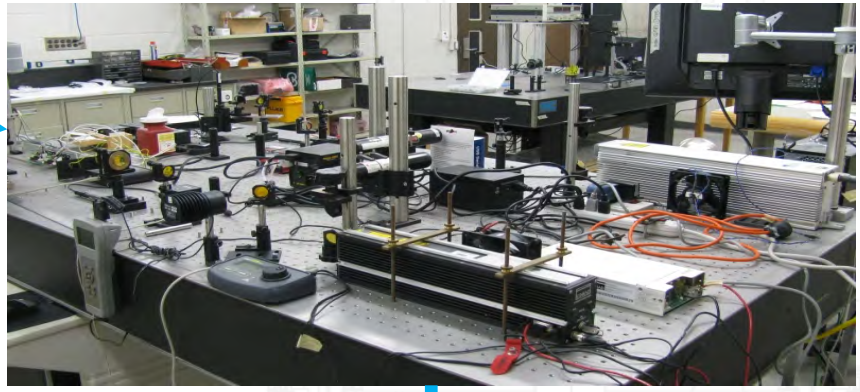
Risk UID	Risk Title
ARD-RSK-001	Image Stability
ARD-RSK-004	Image Quality
ARD-RSK-007	Emergent Behavior

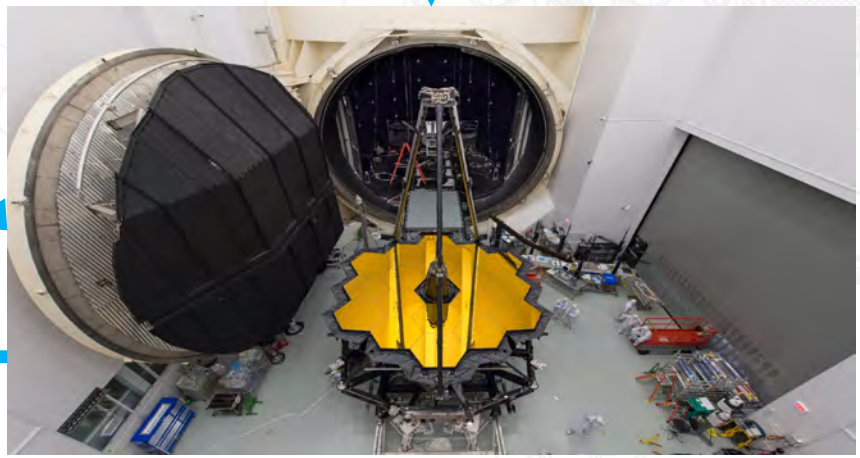
Req. UID	Req. Title
ARD-REQ-009	Camera Operator – Exposure Time
ARD-REQ-014	Image Display – Historical
ARD-REQ-032	Flight Environment - Humidity
ARD-REQ-033	Flight Environment - Temperature
ARD-REQ-034	Flight Environment - Pressure
ARD-REQ-035	Flight Environment - Wind
ARD-REQ-036	Flight Environment - Light Levels
ARD-REQ-037	Flight Environment - Background Light
ARD-REQ-041	Self Environment - Heat Output
ARD-REQ-042	Self Environment - Turbulence
ARD-REQ-062	**Images & Spectra**
ARD-REQ-063	**UV Wavelength**
ARD-REQ-069	**UV Quantum Efficiency**
ARD-REQ-072	**UV Limiting Magnitude**
ARD-REQ-101	Scattered Light
ARD-REQ-109	ARD Focused Light
ARD-REQ-110	ARD Centered Light
ARD-REQ-114	Scientific Configuration Changes
ARD-REQ-116	Add/Remove Observations
ARD-REQ-117	ARD System Component Positions and States
ARD-REQ-119	System Display
ARD-REQ-121	Science Package Display

ARD Test Plan – Incremental Buildup Strategy

ARD-DOC-006 (TPR)

- **Phase 1**: Telescope & Camera on optical bench, Cal Source @ 313nm
- **Phase 2**: Tel/Cam inside **passive** Drone Body, in Env. Chamber, Cal source @ 313nm
- **Phase 3**: Tel/Cam inside **active** Drone, in Env. Chamber, Cal Source @ 313nm





Temperature Range: Controlled, -50 -> +30 degrees Celsius
Wind Speed, Direction: Controlled, 0->20 m/s, 0-359 degs
Pressure: Controlled - 101,325 Pa to 10,317.22 Pa
Humidity: Controlled – 0 -> 100% rH
Lighting: Controlled, Off
Test Duration: 1 week (5 days, 8hr / day)

ARD Test Plan – Desired Results & Metrology

ARD-DOC-006 (TPR)

- **Desired Results**
  - Phase 1:
    - > 80% QE at 313nm
    - Integrated Telescope & Camera Pointing Accuracy
    - Captured Technical Issues
  - Phase 2:
    - > 80% QE at 313nm in simulated environment
    - Test software release & technical fixes
    - Camera Refrigerant temp control
  - Phase 3:
    - > 80% QE at 313nm, in simulated env with drone engines on
    - Measure thermal output of S1.1 Drone Engine subsystem component

Metrology

Metric	Unit	Test Phase	Description
Quantum Efficiency	%	P1, P2, P3	We will use scripts to analyze the delivered Spectra under different environmental conditions during each test phase. This will help to identify if there are any significant impacts from, for example, wind buffeting or thermal emissions that were not properly designed out of the system.
Drone Thermal Emissions	Watts	P3	We use the IR/Thermal camera to quantify the amount of thermal emissions coming from the Drone heat sources such as the battery, engines, CPUs to understand if they will impact the delivered QE.
Acq Time	Secs	P1, P2, P3	By capturing the time it takes to operate the telescope and camera systems and acquire the target, under these best-case test conditions, we can understand where software improvements may need to be made in order to become more efficient in actual operations.
Env – Humidity	rH	P2, P3	Environmental data to be collected at the time of each test. This data will be used for analysis to determine the effect of each environmental variable on the QE of the delivered spectra.
Env – Temp	Deg C	P1, P2, P3	
Env – Pressure	PA	P1, P2, P3	
Env – Wind	m/s	P2, P3	

ARD System Spec – Requirements

ARD-DOC-007 (A-Spec)

- **Activity Description**:
  - **Inputs**: Initial System Level Requirements
  - **Outputs**: "Final" Set of Quantitative System & Subsystem Requirements
- **Process**:
  - Design matures, requirements bound
  - Via stakeholder feedback, research, trade studies, physical design, interface
  - For ARD, the increase in # of Quant. 55% -> 89% and overall reqs went from 110 to 144.

Deliverable	Total	Quantitative	%	Binary	Qual.
Requirements Analysis Report	110	61	55%	49	0
Functional Analysis Report	121	62	51%	59	0
Trade Study	121	62	51%	59	0
Conceptual Design Report	131	99	76%	32	0
Test Plan	131	99	76%	32	0
System Specifications	144	128	89%	16	0

- **Quantitative**:
  - Measurable requirements, performance
  - Example: ARD-REQ-012: "*The ARD shall transmit images and spectra to the remote control station within 1.0 seconds of the image being read-out by the Science Detector.*"
- **Binary**
  - Yes or No requirements
  - Example: ARD-REQ-075: "The ARD shall use software code that is opensource."
- **Qualitative:**
  - Subjective requirements, avoid!
  - Example: "The System shall look cool!"

ARD System Spec – Requirements

ARD-DOC-007 (A-Spec)

- Example ARD-REQ-012:

Initial 9/24/2019:

"The ARD shall transmit images and spectra to the remote control station."

Final 11/11/2019:

"The ARD shall transmit images and spectra to the remote control station ***within 1.0 seconds of the image being read-out by the Science Detector****."*

Deliverable	Total	Quantitative	%	Binary	Qual.
Requirements Analysis Report	110	61	55%	49	0
Functional Analysis Report	121	62	51%	59	0
Trade Study	121	62	51%	59	0
Conceptual Design Report	131	99	76%	32	0
Test Plan	131	99	76%	32	0
System Specifications	144	128	89%	16	0

- **Quantitative**:
  - Measurable requirements, performance
  - Example: ARD-REQ-072: "The ARD shall reach 10th magnitude at 300nm"
- **Binary**
  - Yes or No requirements
  - Example: ARD-REQ-075: "The ARD shall use software code that is opensource."
- **Qualitative:**
  - Subjective requirements, avoid!
  - Example: "The System shall look cool!"

ARD System Spec – KPP Refinement

ARD-DOC-007 (A-Spec)

- **Activity Description**:
  - **Inputs**: Initial set of KPPs
  - **Outputs**: Final set of KPPs
- **Process**:
  - Design matures, KPPs bound and may need changes
  - 3 of 8 KPPs modified, approval from Stakeholders required

KPP ID	KPP Title	KPP Description	KPP Source	Revised?
ARD-KPP-001	**Limiting Mag. – UV**	**The ARD system shall deliver throughput of 80% QE at the Be UV feature at 313nm, with a goal of reaching Boron at 250 nm.**	**Stakeholder Interview**	**11/11/19 – Yes, correction made, added word "system".**
ARD-KPP-002	**Observation in IR**	**The ARD system shall allow a user to take spectra across IR wavelength regime, from 17-37 microns.**	**Initial -Stakeholder Interview Updated to focus on a Jupiter IR interest regime**	**10/10/19 - Yes, added wavelength threshold based on competition with SOFIA**
ARD-KPP-003	Limiting Mag. – Visible	The ARD system shall have a limiting magnitude of V=12.	Stakeholder Interview	No Change
ARD-KPP-004	**Min. Field of View**	**The ARD system shall provide a minimum field of view of 15x15 arcminutes.**	**Stakeholder Interview**	**10/26/19 – updated FOV from 20x20 to 15x15 due to Trade Study Telescope recommendation.**
ARD-KPP-005	Spectra & Imaging	The ARD system shall take both spectra and imaging.	Stakeholder Interview	No Change
ARD-KPP-006	Min. Flight Time	The ARD system shall fly for at least 2 hours.	Stakeholder Interview	No Change
ARD-KPP-007	Min. Flight Altitude	The ARD system shall fly to at least 40,000 feet.	Stakeholder Interview	No Change
ARD-KPP-008	Min. Max Exp. Time	The ARD system shall to have an open shutter exposure time of at least 1800 seconds.	Stakeholder Interview	No Change

Summary & Next Steps

ARD-DOC-009 (Final Report)

- **Summary:**
  - Good Start, **but** still a lot to do…

- **Expand** Stakeholders & SME's
  - Larger group review and revision
- **Revise** Top-Level Requirements
  - Set additional performance requirements
  - Obtain comprehensive and complete set of requirements
- **Hire** Team
  - Deliverables into MBSE model (ARD-RSK-006: Use of Tools).
  - Ensure full traceability – update/revise as needed
- **Conduct** Formal and Informal Trades
  - Formal trades on S1.0 Drone & S3.0 Camera subsystems
  - Focus on modular integration
  - Informal trades optical coatings, power suppliers, software options etc.

- **Add** analysis
  - FEAs for S1.0 Drone Subsystem Payload Environment
  - Raytracing models for telescope/camera optics
- **Create** Failure Modes and Effect Analysis (FMEA)
  - Ensure failure requirements are identified and design decisions made to address any potential failures
- **Expand** ARD Risk Register
  - Define and track mitigation events
- **Expand** Test Plan
  - Include all individual subsystem test cases as well as integration testing for both hardware and software
- **Start** Early Prototyping
  - Focus on more complex or higher risk subsystem components
- **Set** Review Gates
  - PDR, CDR, FDR, V&V Review, Assembly Plan Review etc.
- **Use** Formal Programmatic Tools
  - Formal risk tracking
  - Formal change control tool
  - Formal documentation management tool in order to maintain close version control.

Lessons Learned

ARD-DOC-009 (Final Report)

Lessons Learned UID	Lesson Learned Title	Lesson Learned Description	Date Recorded
ARD-LL-001	**Stakeholder Interviews Preparation**	**I should have provided more of introductory material to my stakeholders before the interviews/questionnaire. I would have gotten more value from their interview answers if they had a more detailed description of what I was going for. For instance, if I had provided a draft ConOps or OV-1 or Context Diagram to each stakeholder ahead of time I think that would have helped get more focused answers.**	**9/21/2019**
ARD-LL-002	Iterative RAR & FAR	It would have been more efficient to work on the Functional Analysis and the Requirements Analysis Report iteratively before submitting the RAR for review. Not only would this have saved me some time overall, but I think that because I submitted the RAR and then focused in on the FAR, the FAR was heavily slanted towards the RAR requirements, rather than if they were developed concurrently it would have provided a more complete and correct set of Functions and Requirements.	9/21/2019
ARD-LL-003	Time Wasted Formatting	I spent a significant amount of my time changing figures, layouts, tabs, copy/pasting from spreadsheets into word documents and back, updating the fonts etc. If I had used a requirements management tool instead of excel that I could have used a macro or function to automatically generate the documents, it would have saved me a significant amount of time and frustration.	9/21/2019
ARD-LL-004	Functional Breakdown L1-2	I found that I didn't have all of the interactions properly defined at the Lvl0 FBD until after going through the exercise of decomposing those functions to get to Level 1,2. I then went back and edited the ARD-F1 FBD Level 0-1. This was a useful lesson learned, as it implies that until you do a breakdown on those level 1 functions you should assume you have missed some information.	9/30/2019
ARD-LL-005	Physical Breakdown	Maintaining the traceability between each level and in each table was difficult. It would have been very useful and saved me time and frustration if I had instead learned how to use a tool that does this a bit more automatically.	11/11/2019
ARD-LL-006	Work/School/Life	It was a very difficult 4 years, balancing work, school and life. I am married with 2 kids under 7, so the lesson learned here is that it would have been great if I had finished this masters before I had kids, or if I had I forced myself to take 3 classes / year from the start to finish the master's program a bit earlier rather than taking 3 semesters in this final year which I knew would also overlap with my family relocating from Tucson Az to La Serena Chile. In addition to this, during the summer semesters where I didn't take classes, I should have used that free time doing preparatory work for the Capstone project, so I could have gotten ahead a bit. In the end I actually wound up finishing the ARD project deliverables a few weeks earlier than I had originally planned, because I used significant vacation time from my job to instead focus on this project.	11/16/2019
ARD-LL-007	Stakeholder Availability	I picked 2 stakeholders from within my own company that I knew were already being overworked. That was a mistake. While they are the experts on their particular fields, I wound up only getting feedback from them on during the initial questionnaire and had to rely on the other 2 stakeholders for the remainder of the project.	11/16/2019
ARD-LL-008	More Iteration	While having the deliverables staggered like this is the right approach for the project, I saw how valuable iteration would become (for instance between the RAR, FAR, and CDR reports). This project is a good start and I can now see the value in iterating on everything, to make sure it is all connected, traced, correct and complete.	11/16/2019
ARD-LL-009	**Keeping Track**	**In a positive lesson learned, I kept a google spreadsheet during this entire project that had all of my requirements, functions, physical components, KPPs, assumptions, these lessons learned, references, N2 etc. This was extremely useful to have one place that was online that I could access from home or work or while on travel, and keep updating as I came up with new ideas. This also made it very easy to just copy/paste from the spreadsheet table into the project deliverable reports (like this table for instance).**	**11/16/2019**

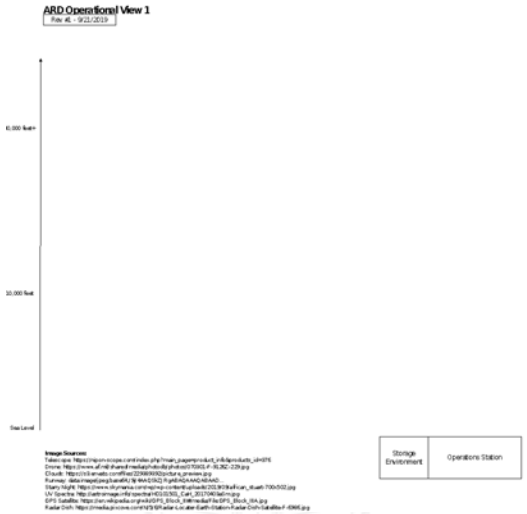
Course Recommendations

- **Recommendation #1**: MBSE, SysML, UML, Req Management Software
  - Much more common in industry now
  - Course would ensure students have good foundational skills and are better equipped to use these programs in their careers
- **Recommendation #2**: More Examples/Case Studies
  - Office hours where professors talk about real experiences are greatly appreciated!
- **Recommendation #3**: Color usage
  - Please have profs use symbols in addition to colors on graphs because not all of us can see all colors!

References

- The template used for this presentation was borrowed from the JHU 645.800 Systems Engineering Project, Fall 2019 Office Hours 12, November 16, 2019. The content is original.

- See individual reports for references



THANK YOU
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QUESTIONS?