
MINERVA
CAL POLY SPACECRAFT DESIGN 2016-2017

MISSION

ARCHITECTURE

OPERATIONS

IMAGING

COMMUNICATIONS

COMMON BUS

LAUNCH

GROUND

MISSION

SECTION 1 OF 8

DREW SAUNDERS

The Customer

The Humphrey and Prudence Tricklebank Foundation was established to support disaster relief activities around the world. Their goal for this mission is to provide satellite assistance to emergency first responders on the ground.

Mission Objective

Provide recurring repeater access and multi-band images of a customer-designated 500 km x 500 km disaster Area of Interest (AOI) within 24 hours of the command time.

Mission Requirements

Schedule

- The system shall reach 25% capability within 12 hours
- The system shall have full capability within 24 hours
- The system shall have 95% capability at 6 months, End-of-Life
- The system cannot be deployed in orbit prior to time of command
- The constellation must deorbit within 5 years after mission completion

Mission Requirements

Imaging

- Provide visible (Vis) and near infrared (NIR) images of AOI with a 5 meter per pixel resolution
- 1 daylight image of entire AOI each day
- 3 daylight images of 15% of AOI (determined by customer) at different times each day (only below 50° latitude)
- Necessity for thermal infrared (TIR) imaging will be decided by customer on day of launch
  - TIR images of 25% of AOI (determined by customer) shall be taken each day
  - Less than 100 meter per pixel resolution
- Images must be provided to customer as quickly as possible

Mission Requirements

Communications

- The system shall provide beyond line-of-sight communications capability to first responders
- The system shall support entire AOI
- The system shall be compatible with existing UHF communications systems
- The system shall provide repeater capability for 240 minutes/day
- The maximum time without repeater access is 120 minutes
- The minimum communications window is 3 minutes

Mission Requirements

Launch/Ground

- The systems shall operate in politically stable locations
- The systems shall comply with applicable U.S. and international regulations
- The systems must store for at least 5 years prior to launch
- The system cannot utilize existing government or military infrastructure

Mission Scope

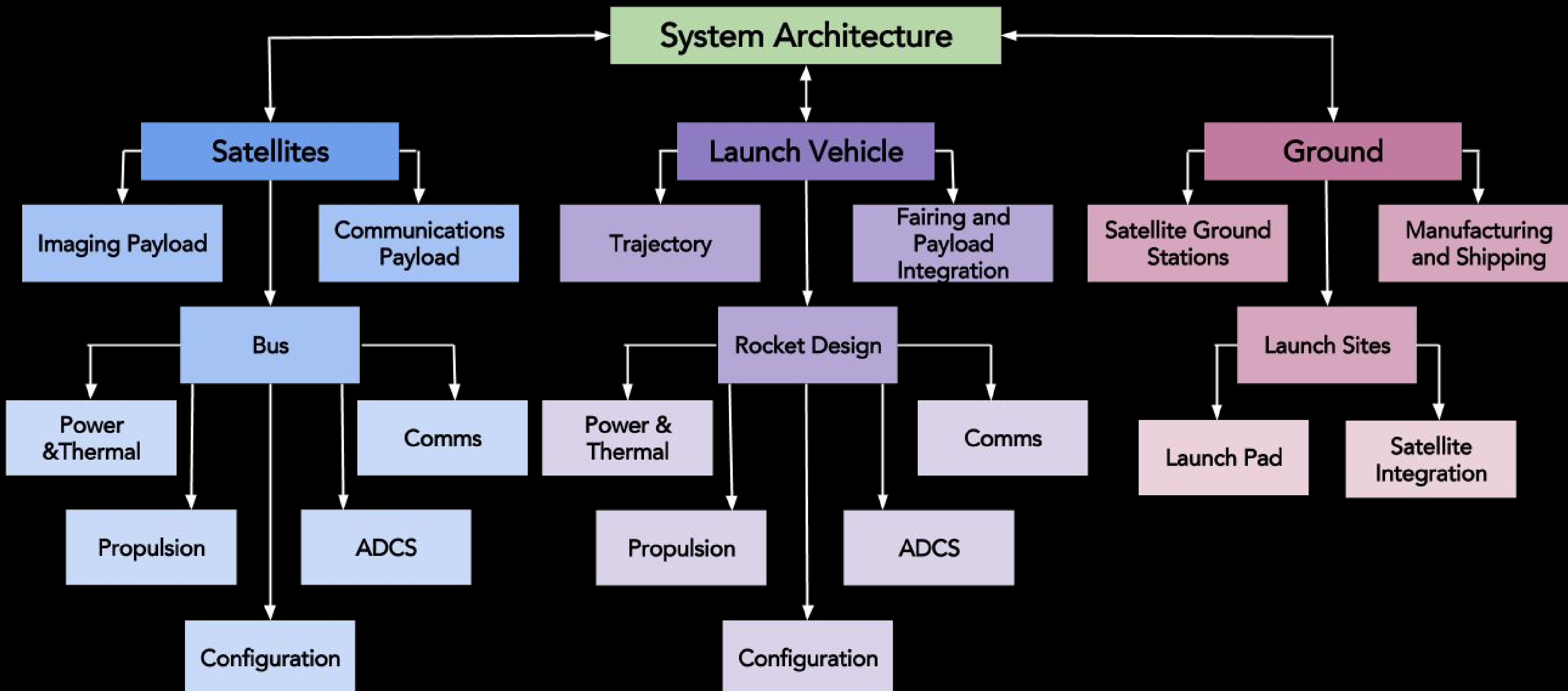
We are required to complete:

- Full design of satellites, launch vehicle, and launch pad
- Full concept of operations
- Know locations and requirements for all ground stations and launch sites
- Integration, test, manufacturing, and shipping plans

Beyond the scope of the project:

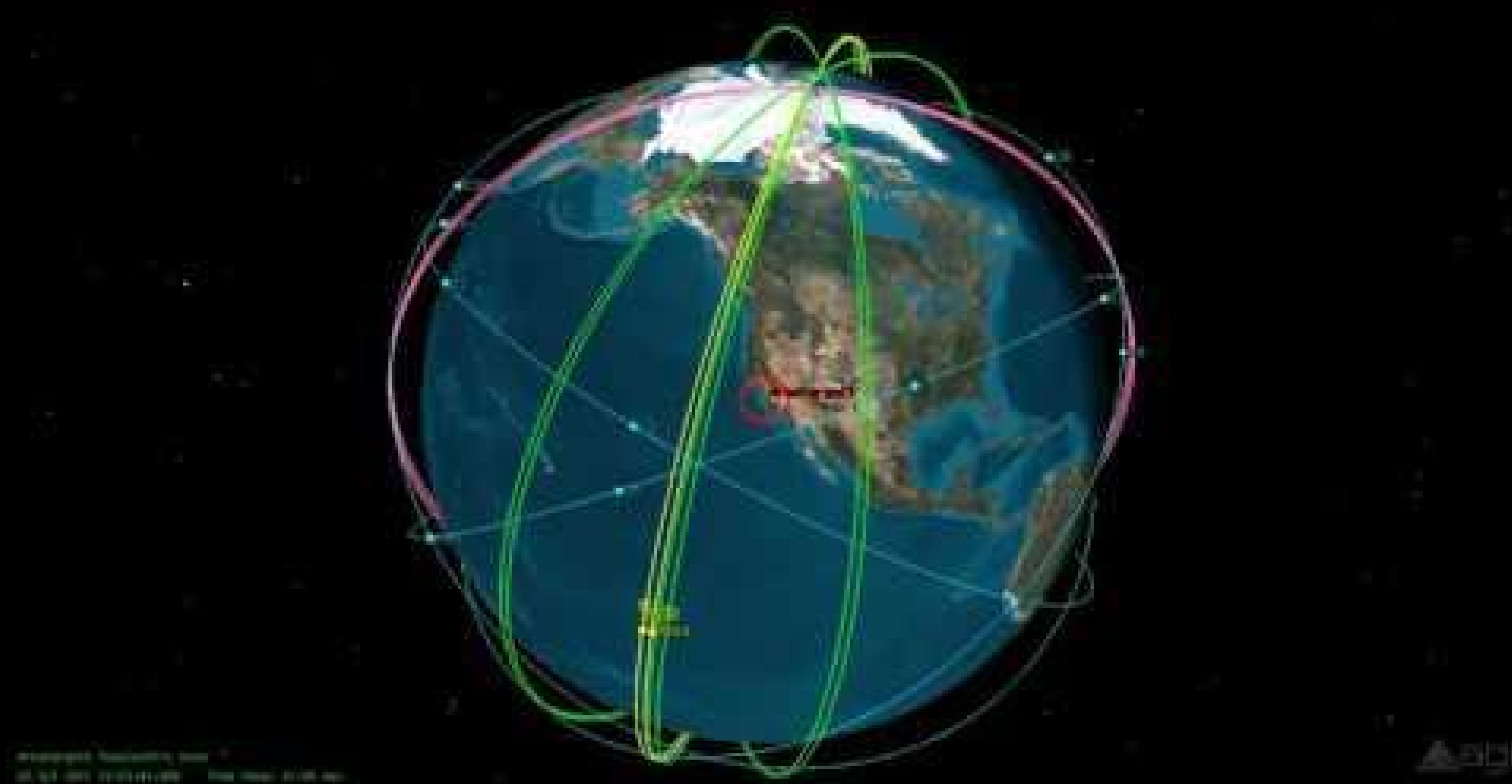
- Any software design
- Fixing or solving any legal and regulatory obstacles

Class Organization




ARCHITECTURE
SECTION 2 OF 8

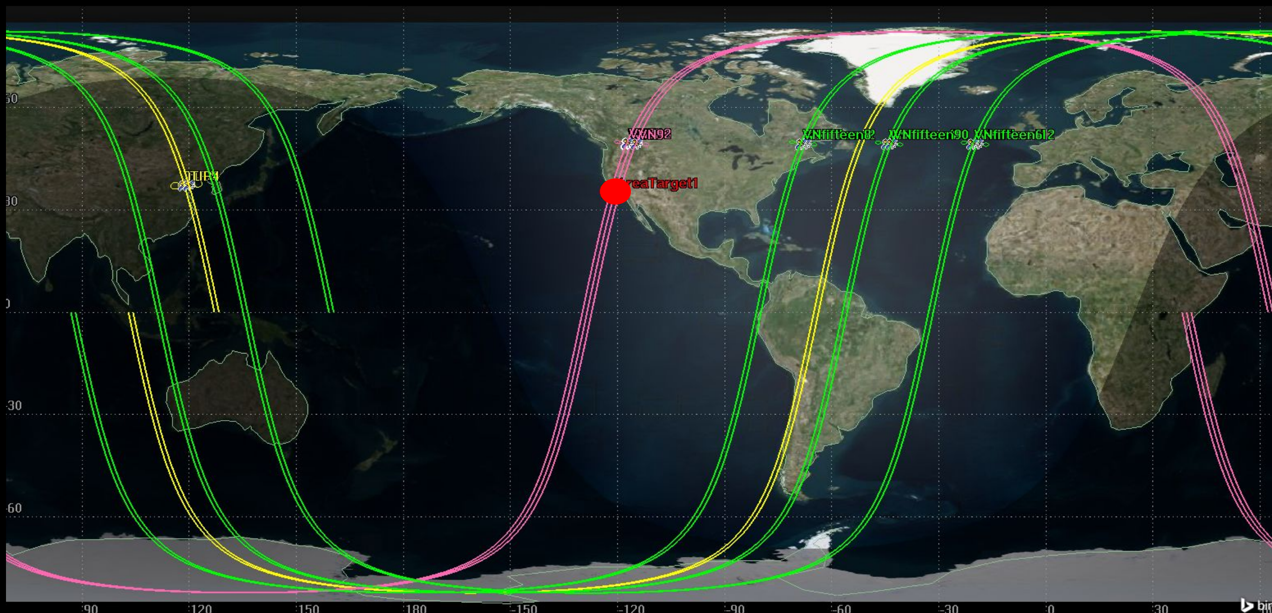
System Introduction



Mission Trades

Trade	Outcome
Orbital Altitude	LEO
Capability Allocation	Separate Satellites
Orbital Variability	Variable Orbits
Distribution Scheme	Capability on Satellites
Spectral Band Allocation	Separate Vis/NIR and TIR Satellites
Common Bus	Satellites Have Common Bus

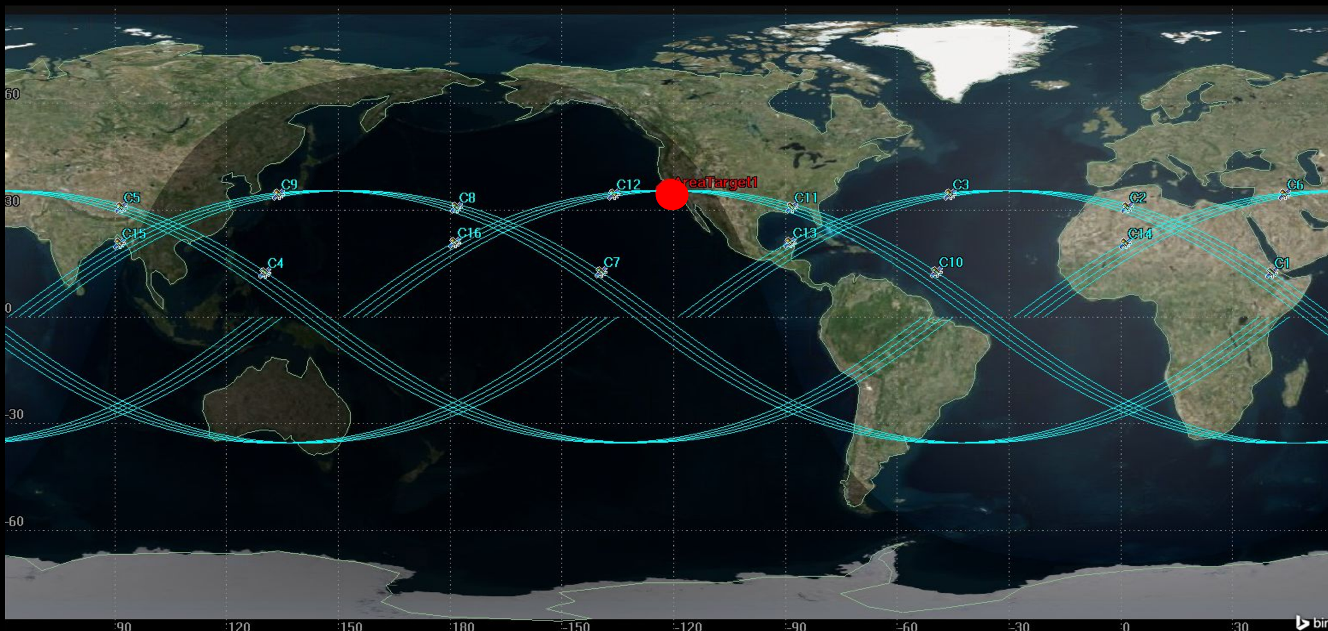
Imaging Architecture



RED = Target Area
PINK = Full Image Vis/NIR
GREEN = 15% Vis/NIR
YELLOW = 25% TIR

- **11** planes, **28** satellites
  - **12** sats/full image, Vis/NIR
  - **4** sats/15% image, Vis/NIR
  - **4** sats/25% image TIR
- Circular, **sun-synch 567 km** altitude, **repeat ground track orbits**
- Satellite groups dispersed in RAAN

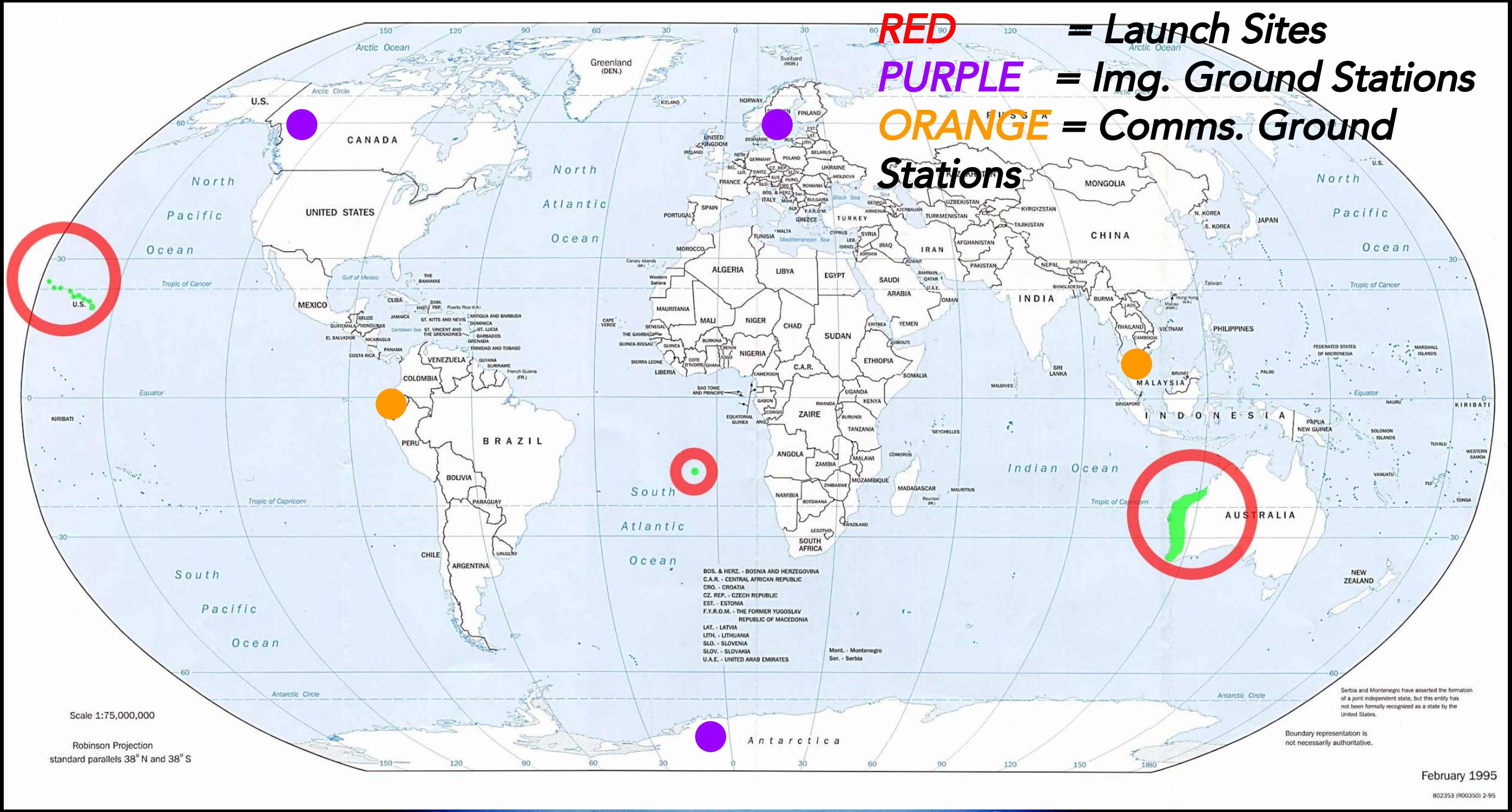
Communications Architecture



***RED* = Target Area**
***BLUE* = Satellite Ground Tracks**

- **4** planes, **16** satellites
  - **4** sats/plane (total)
- Circular **625 km** altitude, **latitude-inclination matching**
- Planes equally spaced in RAAN
- Satellites spaced **40** degrees apart in true anomaly

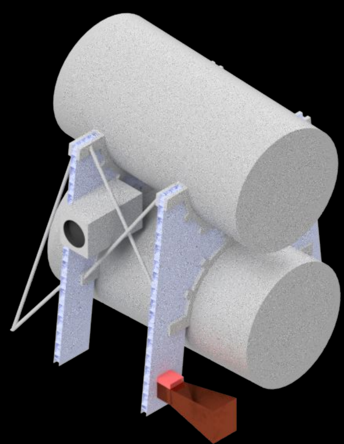
Ground Operations Locations



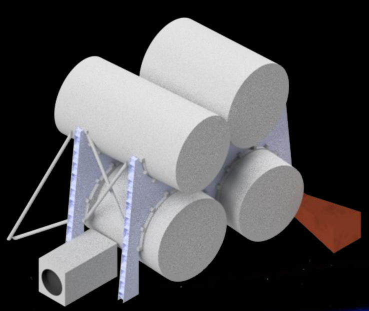
Common Bus

Interchangeable Payloads

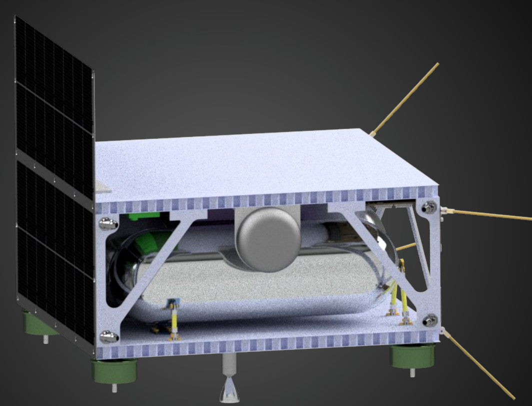
Vis/NIR Payload



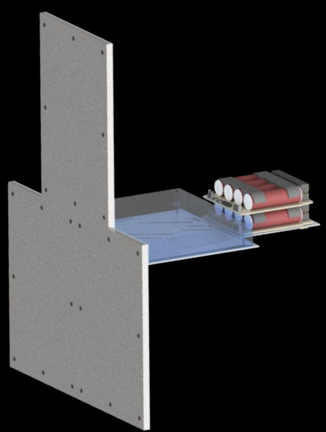
TIR Payload



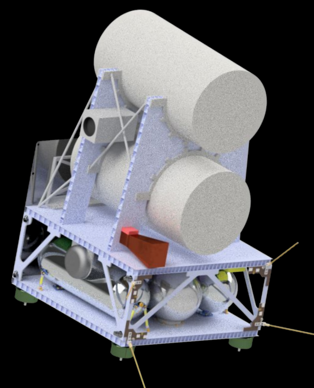
Common Bus



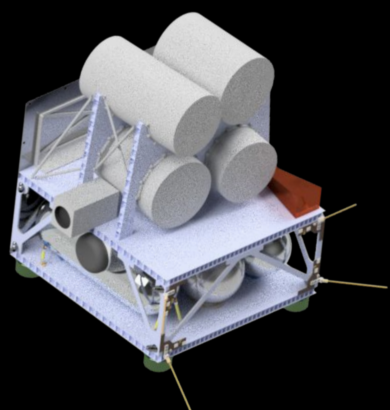
Comms Payload



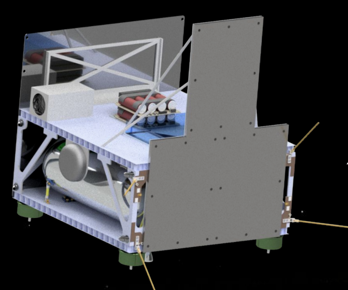
System Summary



X 24
25 kg



X 4
25 kg

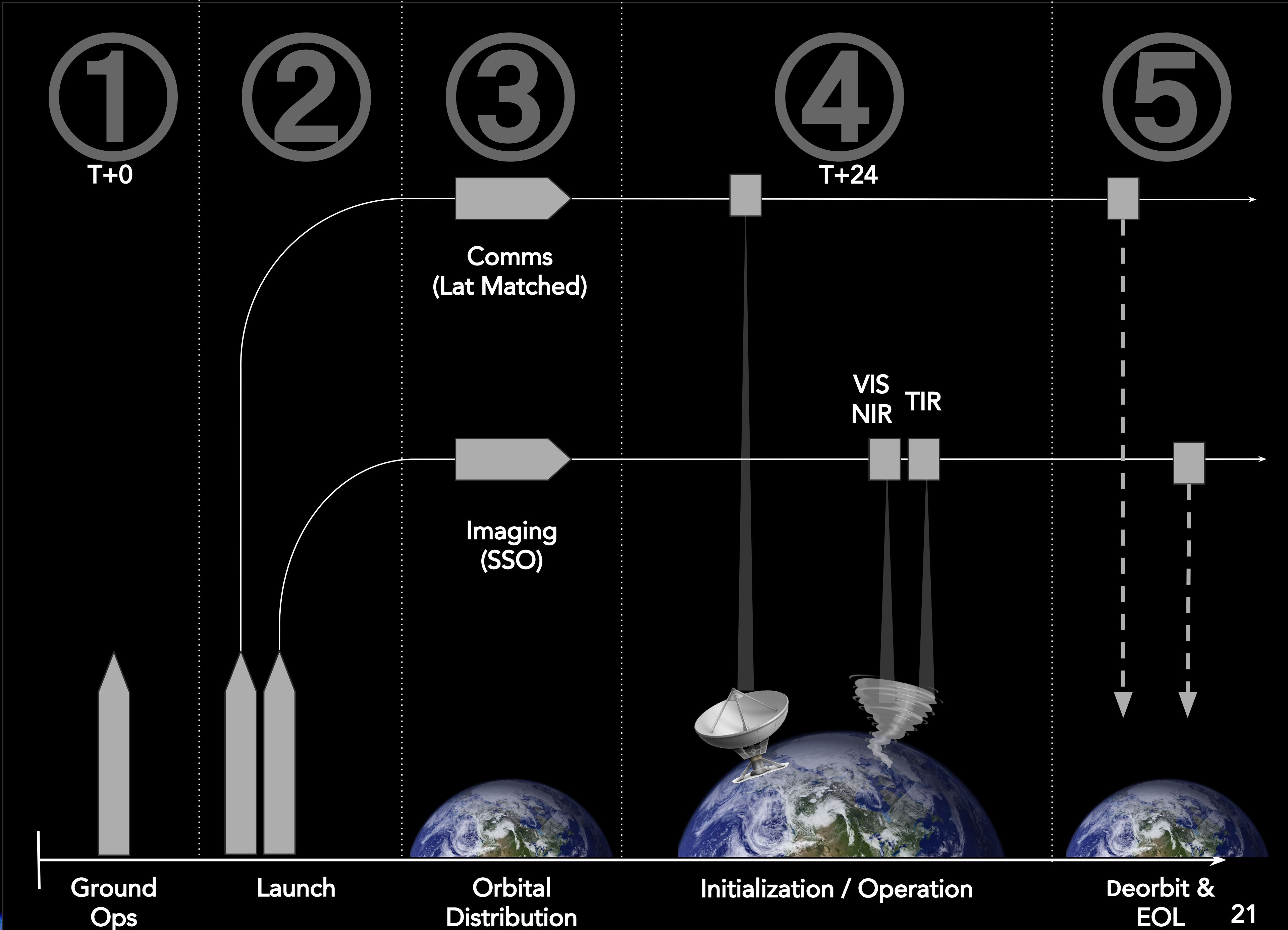


X 16
12 kg

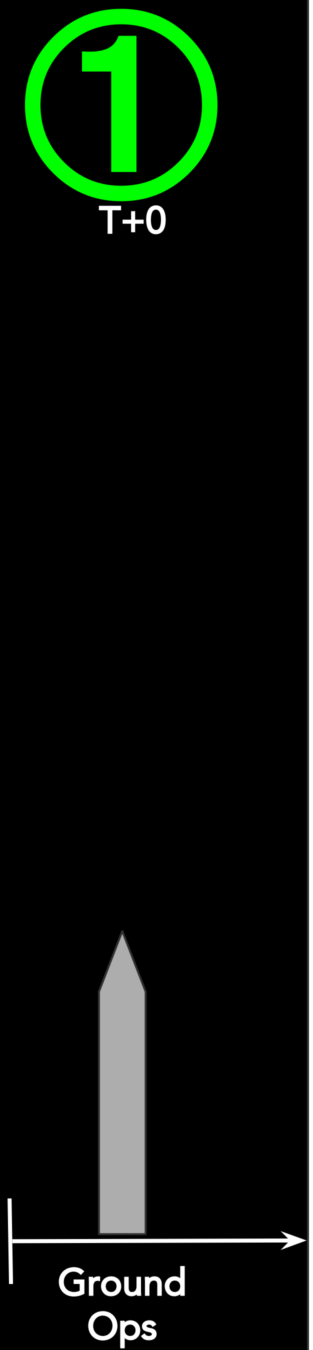
X 11
25 tonnes

OPERATIONS

SECTION 3 OF 8

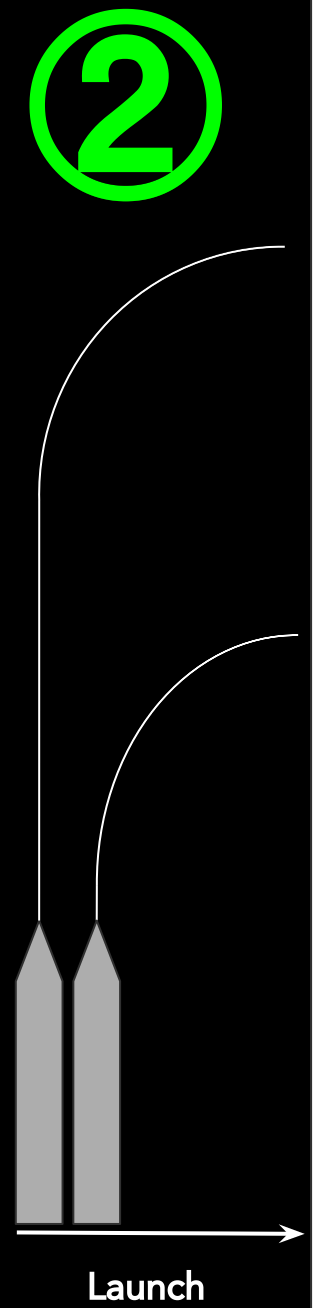


T+0
T+24
Comms
(Lat Matched)
Imaging
(SSO)
VIS
NIR
TIR
Ground
Ops
Launch
Orbital
Distribution
Initialization / Operation
Deorbit &
EOL



Pre-Launch Operations

- 5 year storage capability
  - Fully fueled launch vehicles
  - Satellites fueled integrated
- Program trajectories
- Satellite startup
  - Health checks, testing



Launch

- Launch considerations
  - Parameters affected by AOI latitude
  - Launch order and windows
- Elliptical transfer orbit insertion for phasing

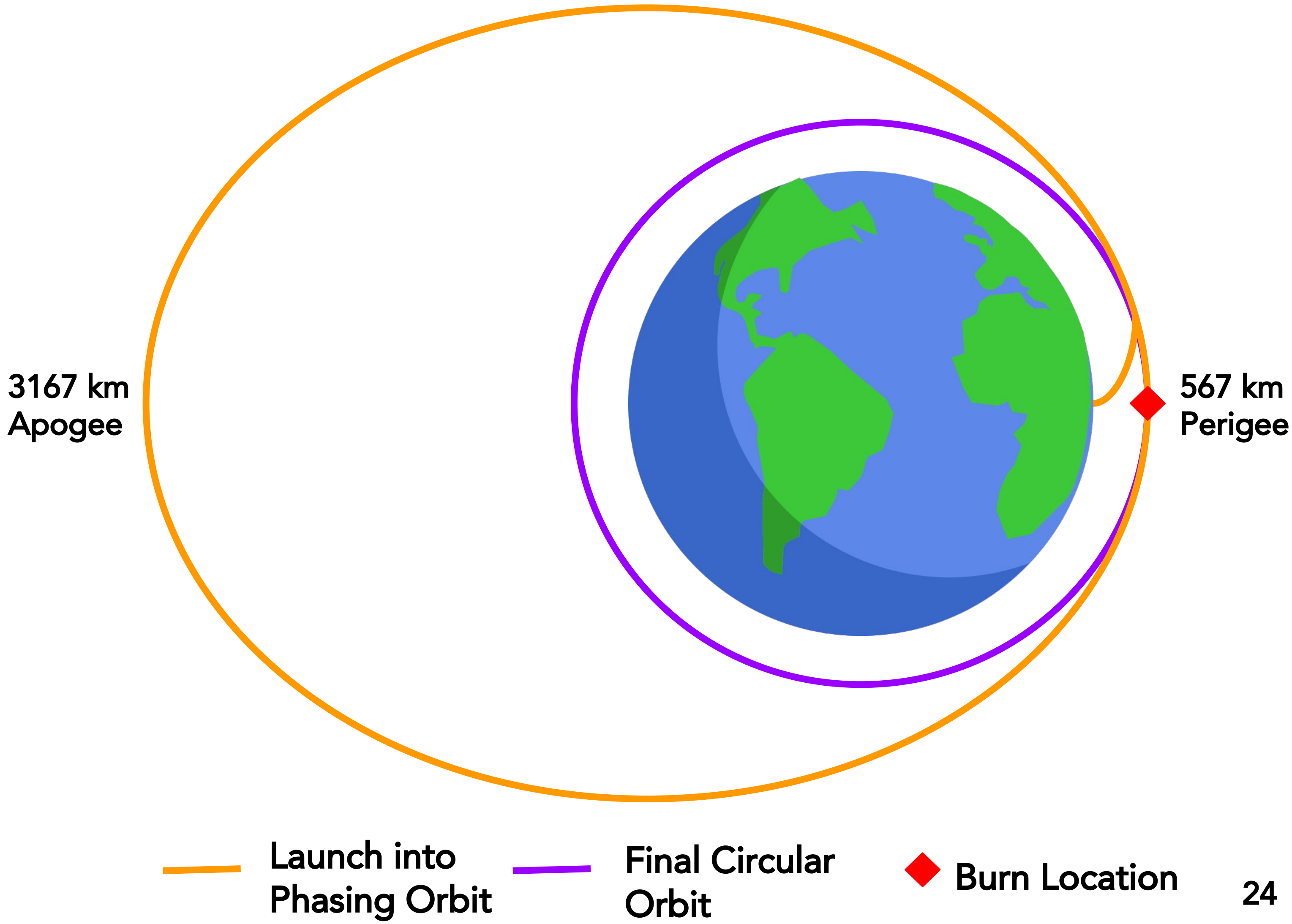
3

Comms
(Lat Matched)

Imaging
(SSO)

Orbital
Distribution

Orbital Distribution - Imaging



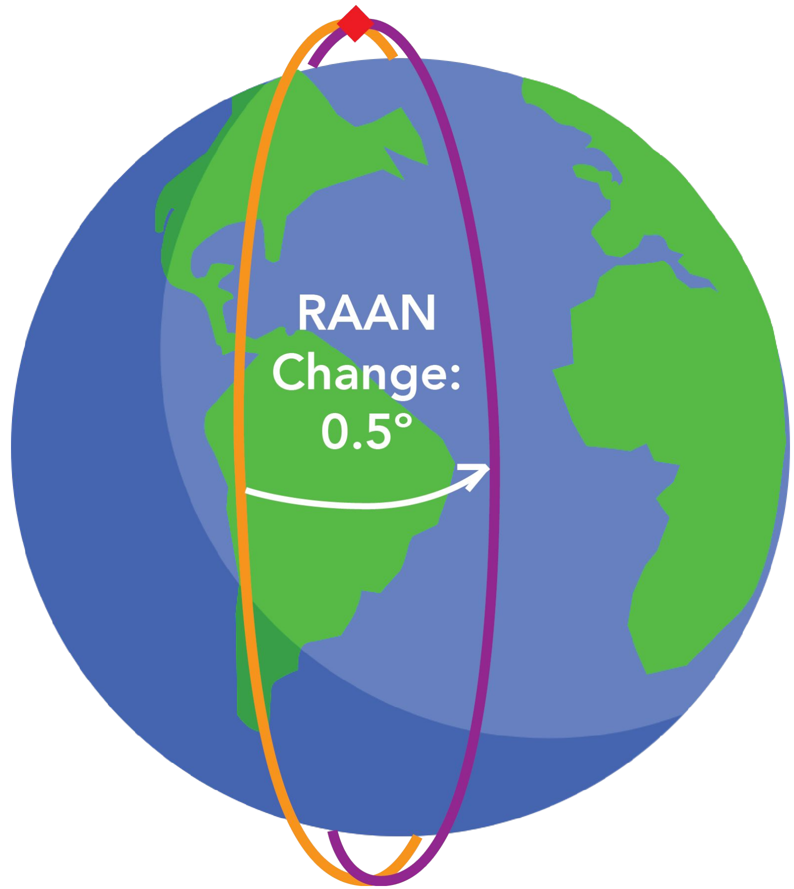
3

Comms
(Lat Matched)

Imaging
(SSO)

Orbital
Distribution

Orbital Distribution - 15% Vis/NIR and TIR Imaging



Circular Orbit for First 2 Satellites

Circular Orbit for Second 2 Satellites

Burn Location

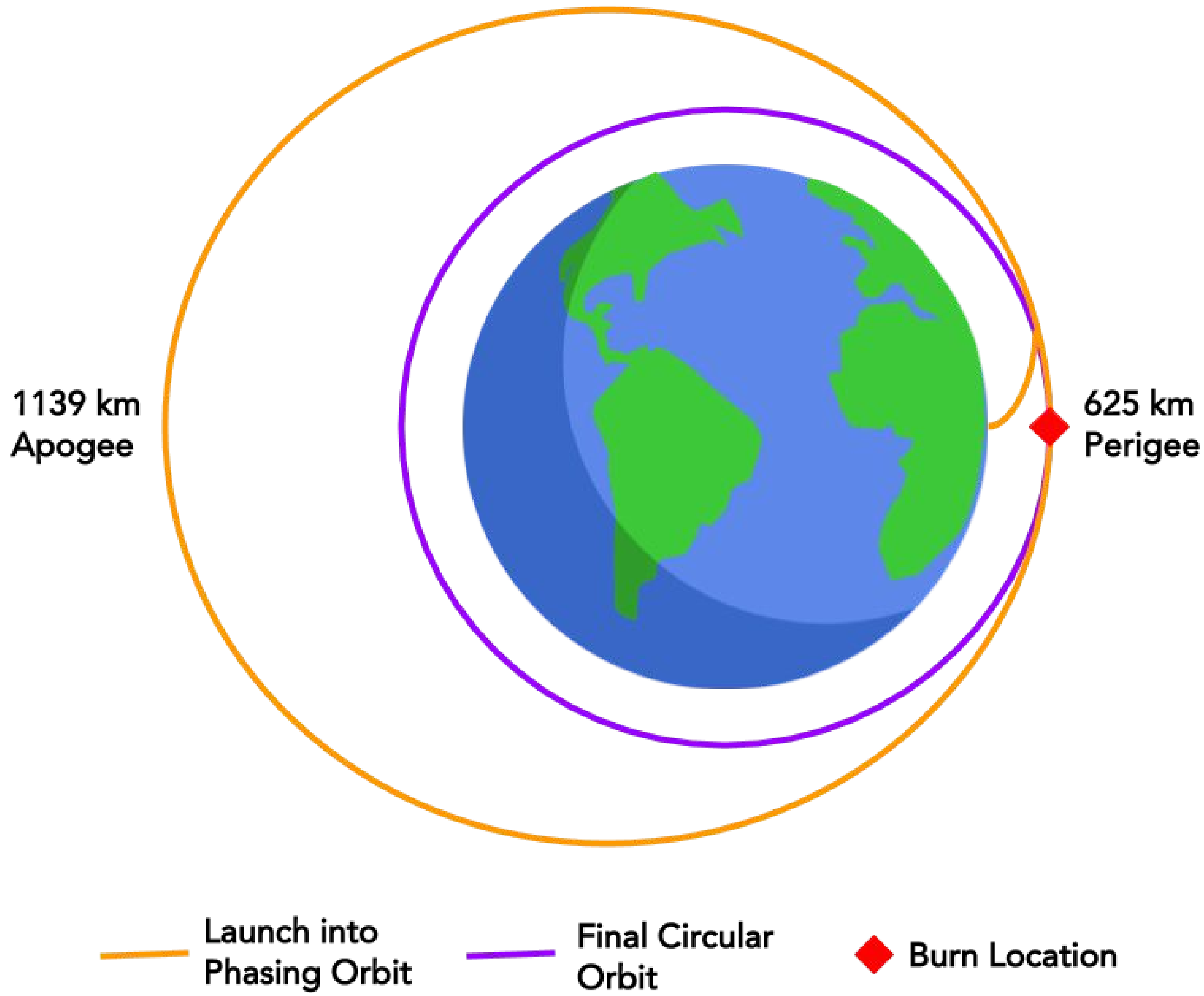
3

Comms
(Lat Matched)

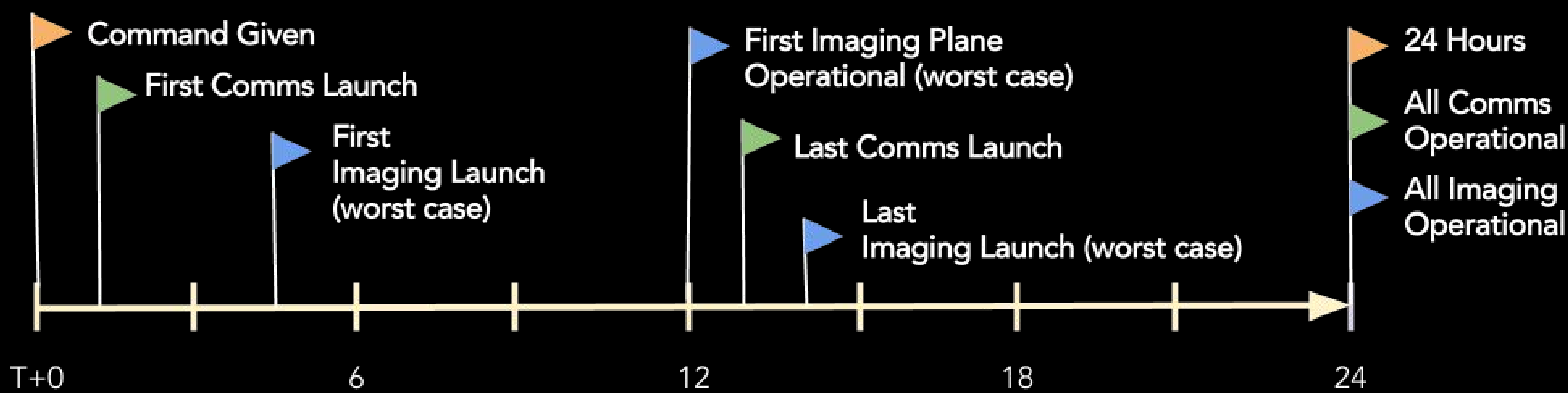
Imaging
(SSO)

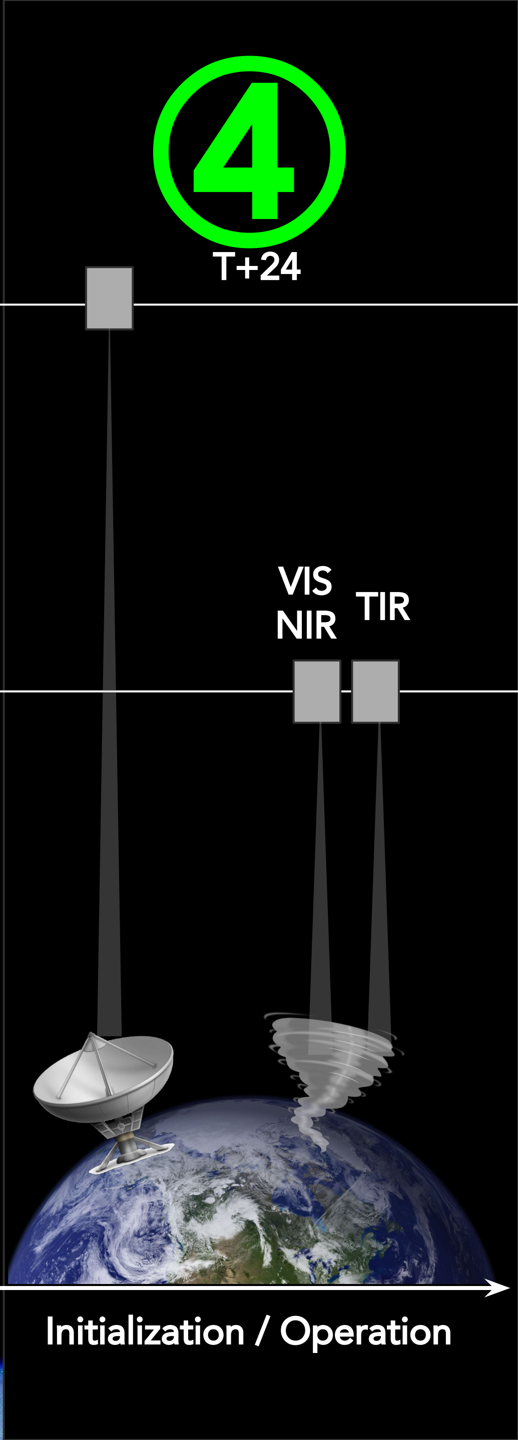
Orbital
Distribution

Orbital Distribution - Communications



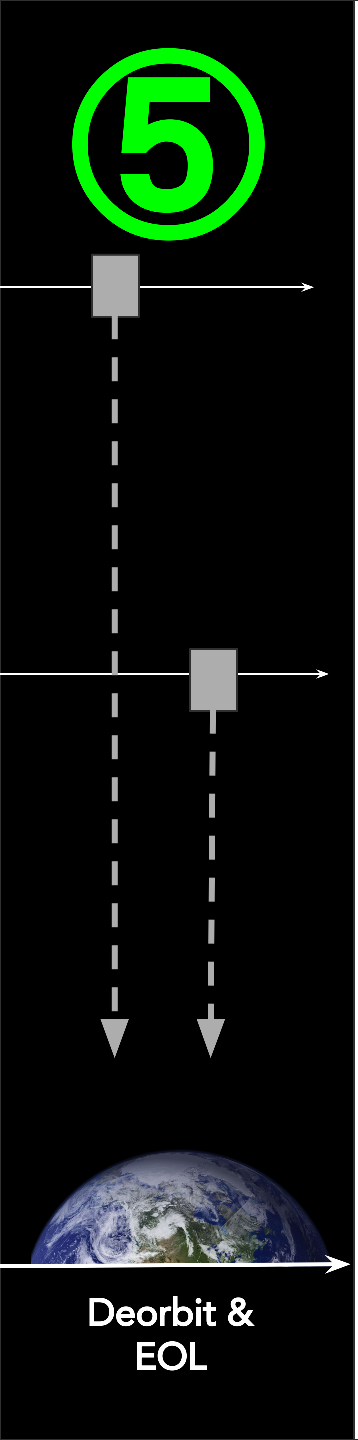
24 Hour Timeline





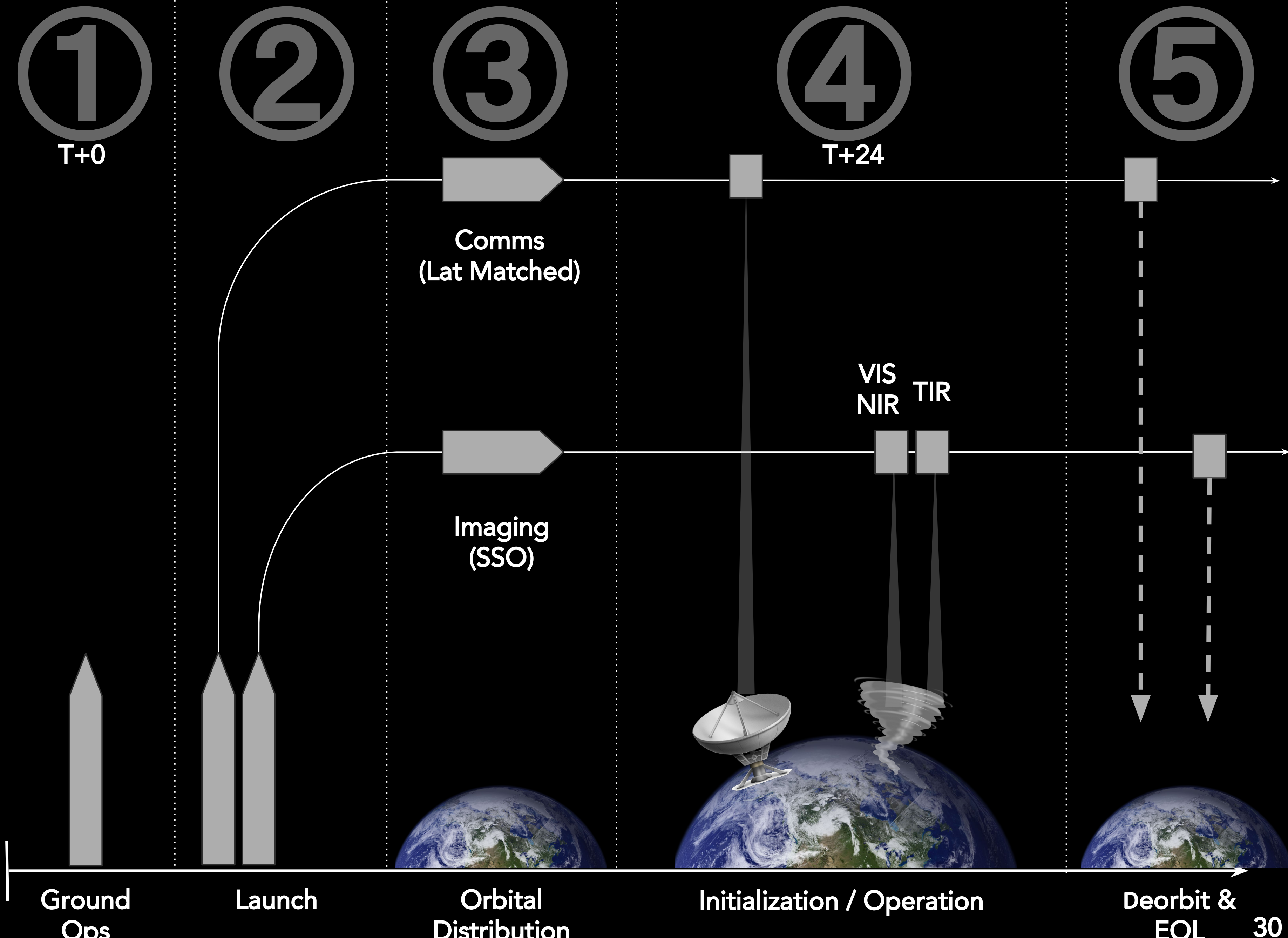
Initialization/Operation

- Satellites conduct daily operations to fulfill requirements
  - Communications provide repeater access
  - Imaging receive commands and image designated areas



Deorbit & End of Life

- Satellites burn to drop altitude to deorbit within the 5 year requirement
  - Drop perigee to 450 km



①
②
③
④
⑤
T+0
T+24
Comms
(Lat Matched)
VIS
NIR
TIR
Imaging
(SSO)
Ground
Ops
Launch
Orbital
Distribution
Initialization / Operation
Deorbit &
EOL

IMAGING

SECTION 4 OF 8

BRANDON URENO

System Requirements

- Image Visible (Vis), Near IR (NIR), and Thermal IR bands (TIR)
- Resolution
  - Vis/NIR - 5 m per pixel
  - TIR - 100 m per pixel
- Vis/NIR
  - 1 daylight image of entire AOI each day
  - 3 daylight images of 15% squares of AOI (only below 50°)
- TIR (if deemed necessary by customer)
  - up to 25% of AOI composed of a minimum of 5% squares

Major Trades

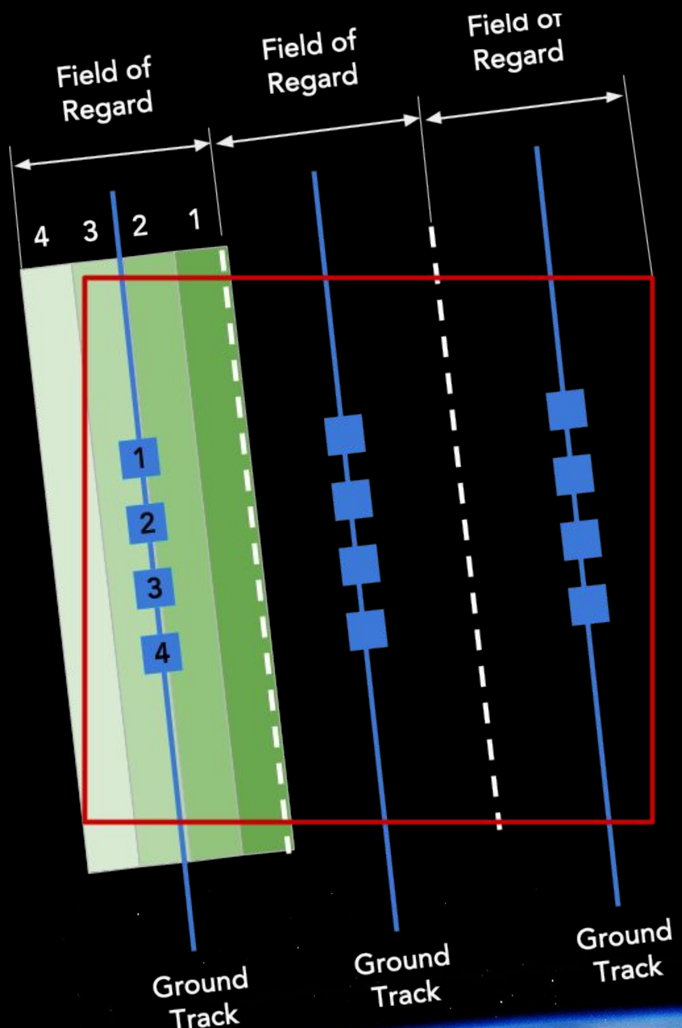
Trade	Status	Outcome
Orbits	Closed	Sun-sync repeat ground track
Sensor Type	Closed	<u>Pushbroom Scanner</u>
Satellite Capability	Closed	<u>Vis/NIR: 62.6 km swath</u> <u>TIR: 153.6 km swath</u>
Planes per Group of Auxiliary Images	Closed	2 Planes
Downlink Antenna	Closed	Ku band horn
ACS	Closed	Cold Gas Thrusters

Imaging Scheme

Orbits Overview

- Full Image Groups (Vis/NIR)
    - 3 planes with 4 sats per plane
- 15% Groups (Vis/NIR) and 25% Group (TIR)
    - 2 planes with 2 sats per plane
        - Vis/NIR has 3 of these groupings to take the 3 15% images
        - TIR has 1 of these groupings to take the 25% image

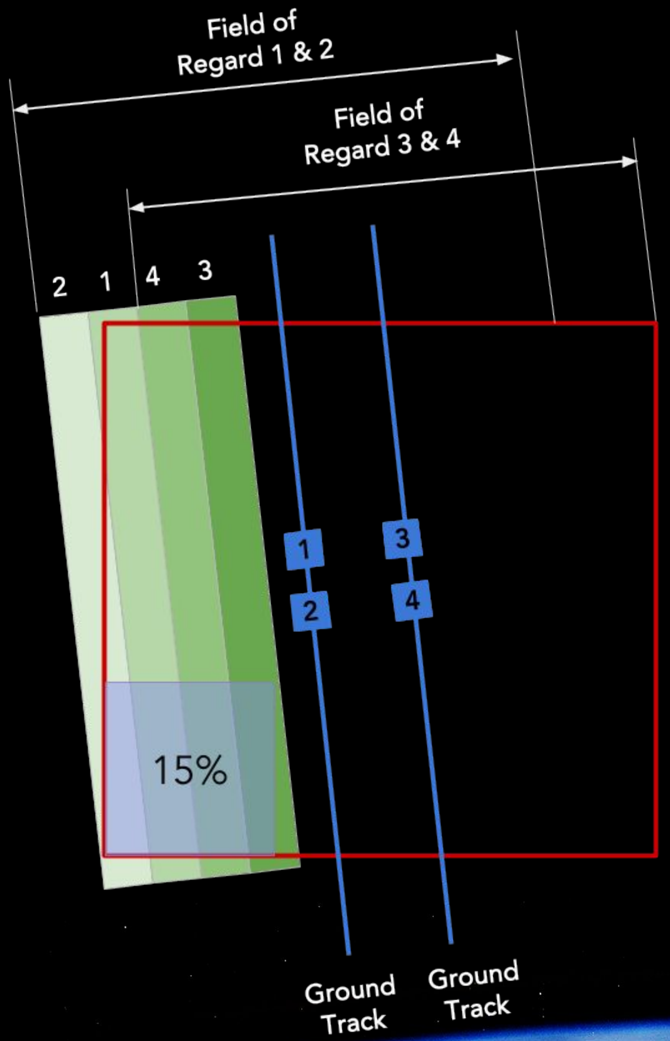
Imaging Scheme



Vis/NIR Full Image

- Max off-nadir slew: 13.5 deg
- Swath width: 62.6 km
- Overlap: 5% between swaths

Imaging Scheme



Vis/NIR 15% Image

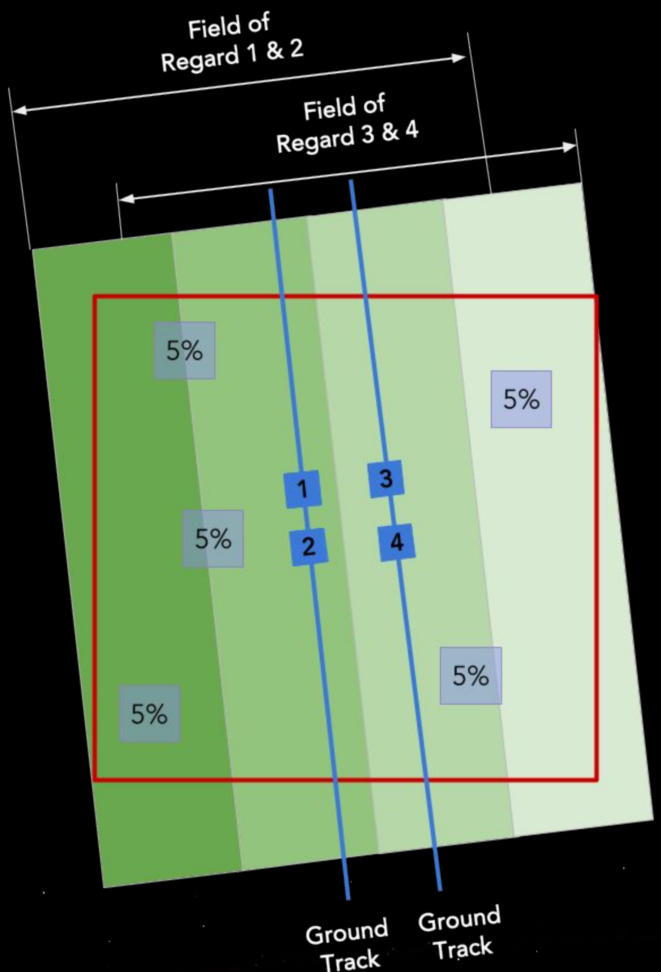
- Max off-nadir slew: 18.5 deg
- Swath width: 62.6 km
- Overlap: 5% between swaths

Imaging Scheme

Orbits: Vis/NIR Summary

Latitude	0° - 50°	50° - 70°	70° - 90°
Orbit Type	Sun-Synchronous Repeat Ground Track	Sun-Synchronous Repeat Ground Track	Polar Repeat Ground Track
Altitude	567 km	567 km	554 km
Inclination	97.7°	97.7°	90°
No. of Planes	9	3	3
Total No. of Satellites	24	12	12

Imaging Scheme



TIR 25% Image

- Max off-nadir slew: 14 deg
- Swath width: 153.6 km
- Overlap: 3% between swaths
- 25% could be divided into as many as five areas

Imaging Scheme

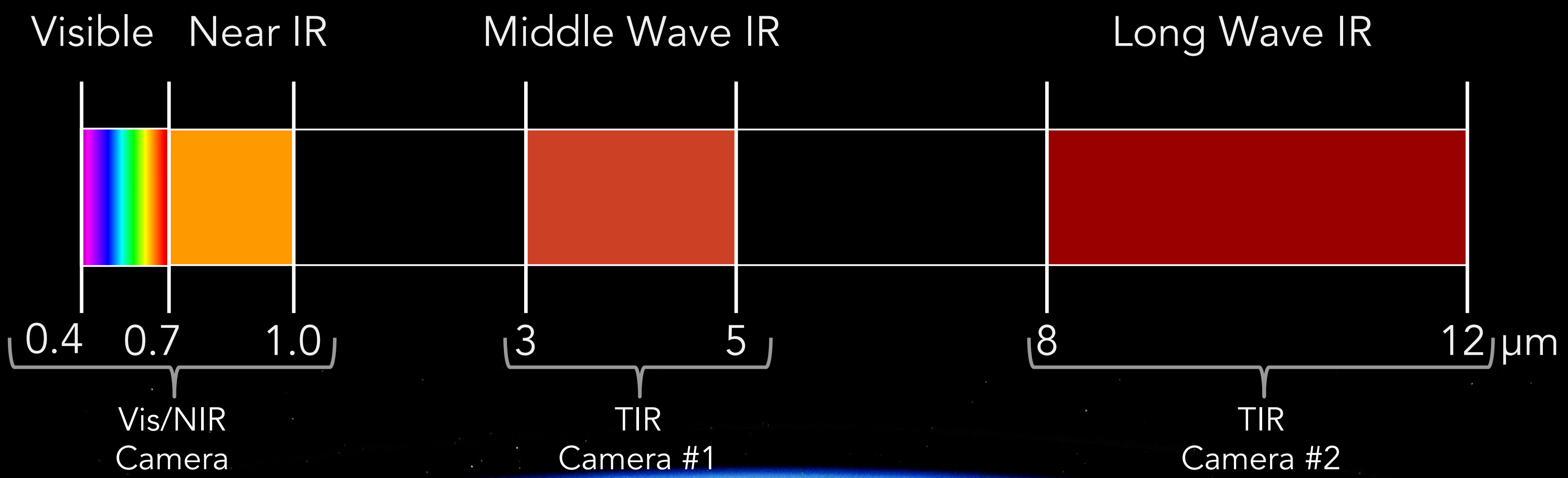
Orbits: TIR Summary

Latitude	0° - 70°	70° - 90°
Orbit Type	Sun-Synchronous Repeat Ground Track	Polar Repeat Ground Track
Altitude	567 km	554 km
Inclination	97.7°	90°
No. of Planes	2	
Total No. of Satellites	4	

Optical Payload

Spectral Bands

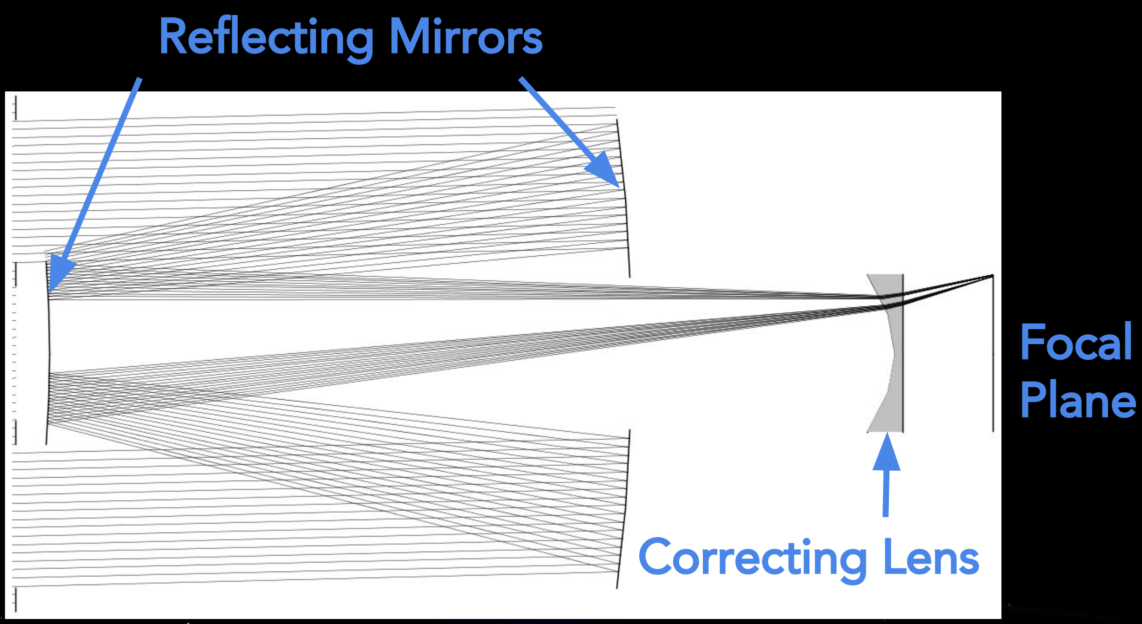
- Visible
  - 0.4-0.7 µm
- Near IR
  - 0.7-1.0 µm
- Middle Wave IR
  - 3-5 µm
- Long Wave IR
  - 8-12 µm



Optical Payload

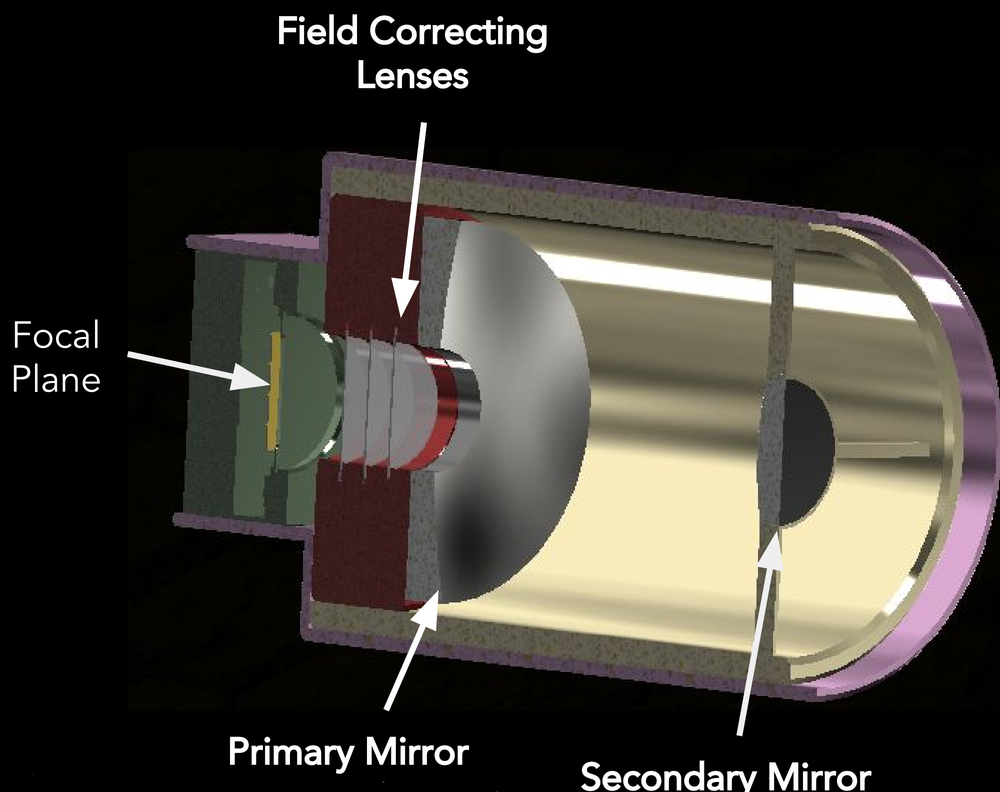
Vis/NIR: Telescope and Sensor

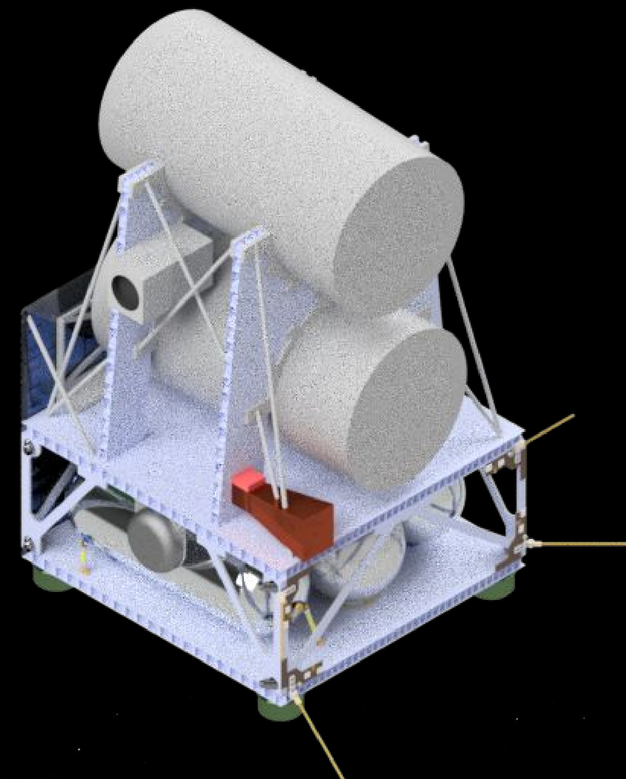
- Reflecting telescope (2 per satellite)
  - Cassegrain (Ritchey Chretien) design
  - Field correcting lens system
  - Dimensions: ∅18 cm x 35 cm



Optical Payload

Vis/NIR: Configuration





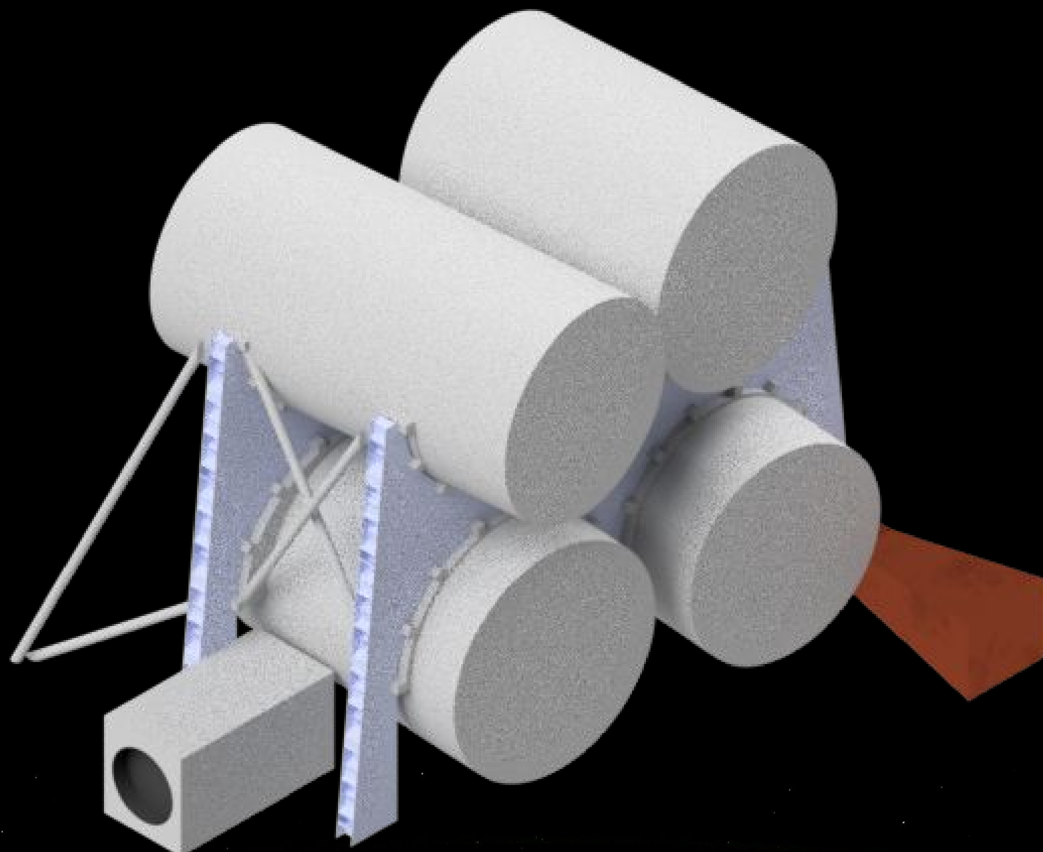
Optical Payload

TIR: Telescope and Sensors

- Refracting Telescope (4 per satellite)
    - 16 Lens Fixed Focal Lens
    - Middle Wave: ∅11.5 cm x 21.5 cm
    - Long Wave: ∅12.5 cm x 16 cm
- Pyroelectric detectors
    - Uncooled
    - Shutter required

Optical Payload

TIR: Configuration



Subsystems and Budgets

ADCS: Attitude Determination

- Attitude knowledge requirement: 0.03 degrees
- Fine knowledge required during imaging phase only

	Imaging	Downlink	Sun-Tracking
Pointing Requirement (deg)	0.3	7.5	10
Slew Rate (deg/s)	0.07	0.765	0.005

Imaging - ADCS Pointing Budget

Subsystems and Budgets

Communications:
Image Downlink

- On-board system for downlinking:
  - Ku-Band
  - Wideband horn
  - BPSK modulation

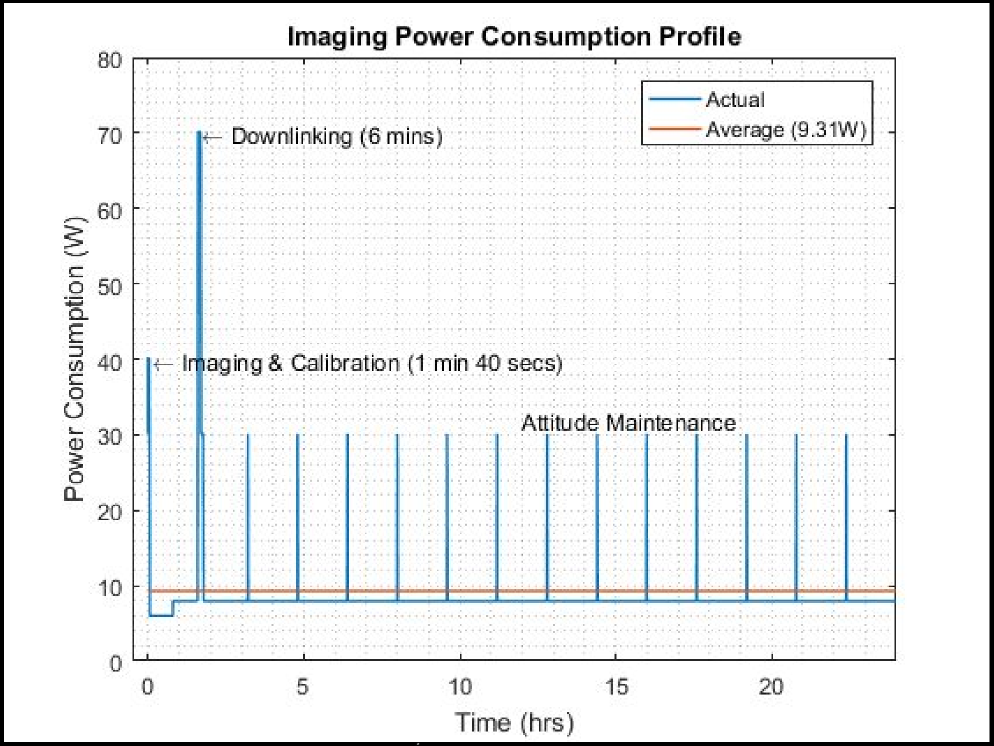
Link Budget Downlink of Images	
Data Rate	200 Mbps
Gain of Transmitter	14 dB
Gain of Receiver	48 dB
Power (RF)	10 W
Margin	4.3 dB

Imaging Comms Downlink

Subsystems and Budgets

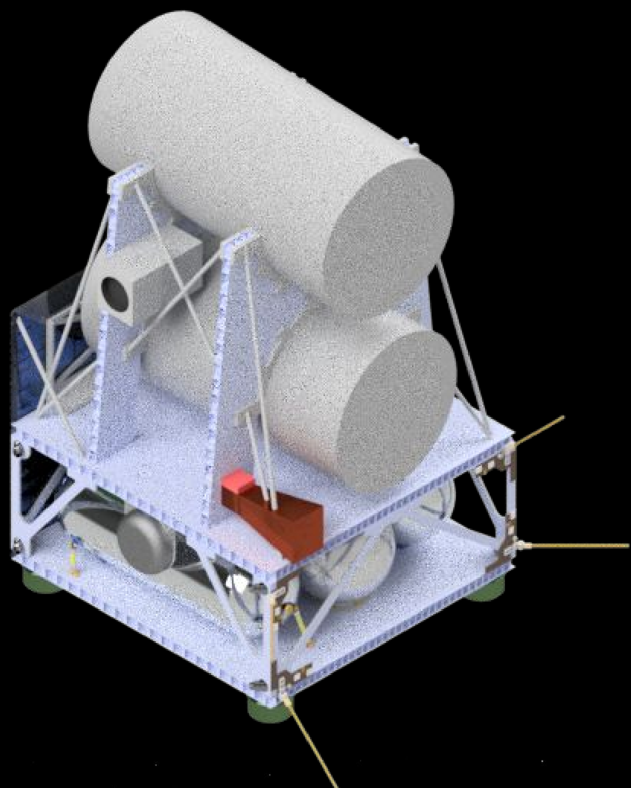
Power : Operations Cycle

Orbit	Operation	Net Battery Change (W-hr/orbit)
1	Imaging collection & processing	-13.07
2	Downlinking	-20.8
3-14	Power generation	+143
15	Power generation & orbital maintenance	+10

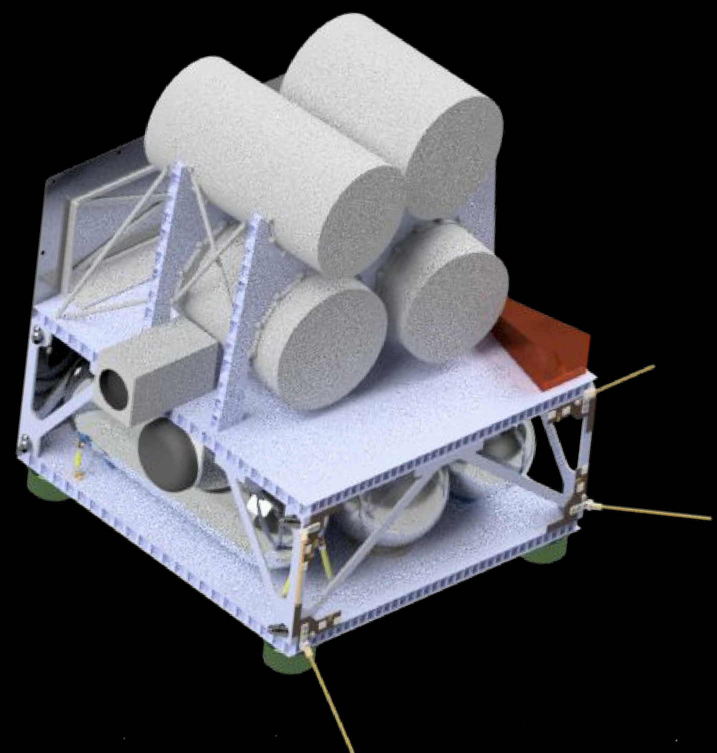


Configuration

Payload and Bus



Vis/NIR Satellite



TIR Satellite

COMMUNICATIONS

SECTION 5 OF 8

JACOB LLEWELLYN

System Requirements

- Repeater Capability
  - 240 min/day
  - Maximum 120 minutes without Repeater Access
- Communications
  - Beyond line-of-sight to first responders
  - Minimum communications window of 3 minutes.

Major Trades

Trade	Status	Outcome
Orbit Altitude	Closed	625 km
Variable vs. Invariable Orbits	Closed	Variable
Antenna Type	Closed	3 patch antennas (2 receiver and 1 transmit)

Orbits

Constellation Parameters

Altitude	Inclination	RAAN Spacing (Planes)	True Anomaly Spacing (Satellites)	Eccentricity
625 km	Latitude	Equal	40°	0

Constellation Scheme vs Coverage Latitude

Latitude Bin	0°-10°	10°-25°, 65°-90°	25°-65°
No. of Satellites	16	12	16
No. of Planes	4	3	4

*0-16° covered by 16° inclination from St. Helena launch site

Repeater Operations

- Harris XL-200P handheld radio for first responders
  - AES/DES encryption used to ensure communication occurs only in the AOI
- Text communication for easier use and better reliability
- Channel scheme fits within the existing US National Interoperability Plan
  - Total of 6 channels each with 12.5 kHz bandwidth
- Frequencies can be adjusted based on the country where the disaster occurs

Repeater Payload

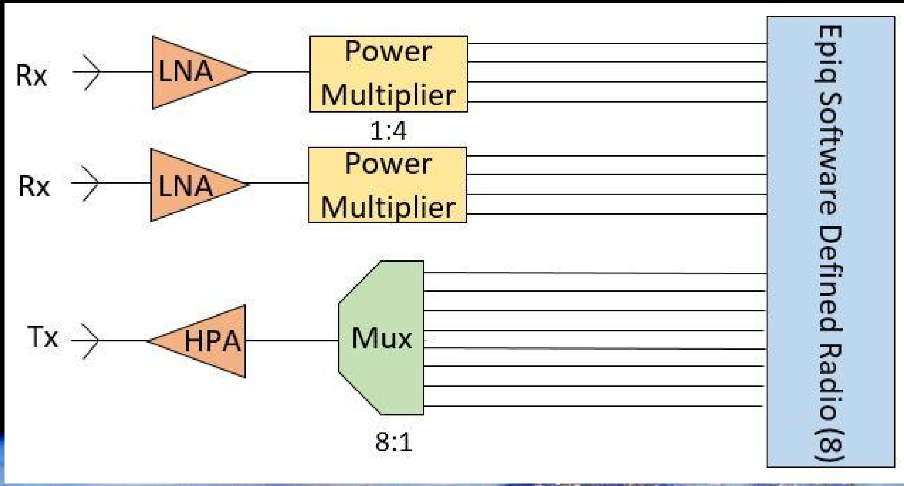
Payload Design: UHF Repeater

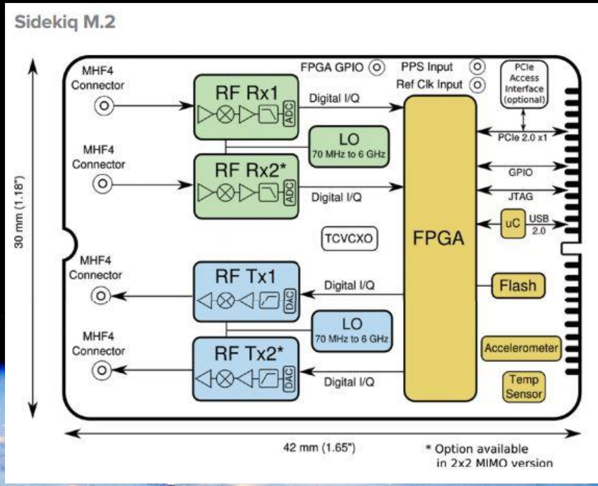
- Multiple Software Defined Radios (SDR)
  - Large frequency variability
  - Counteracts doppler shift
- Multiplexing: Frequency Division
  - Full duplex system
- Multiple Access Scheme: Frequency Division
  - Easiest, fastest
- Modulation: Frequency Shift Keying
  - Available on a handheld radio

Repeater Payload

Payload Components

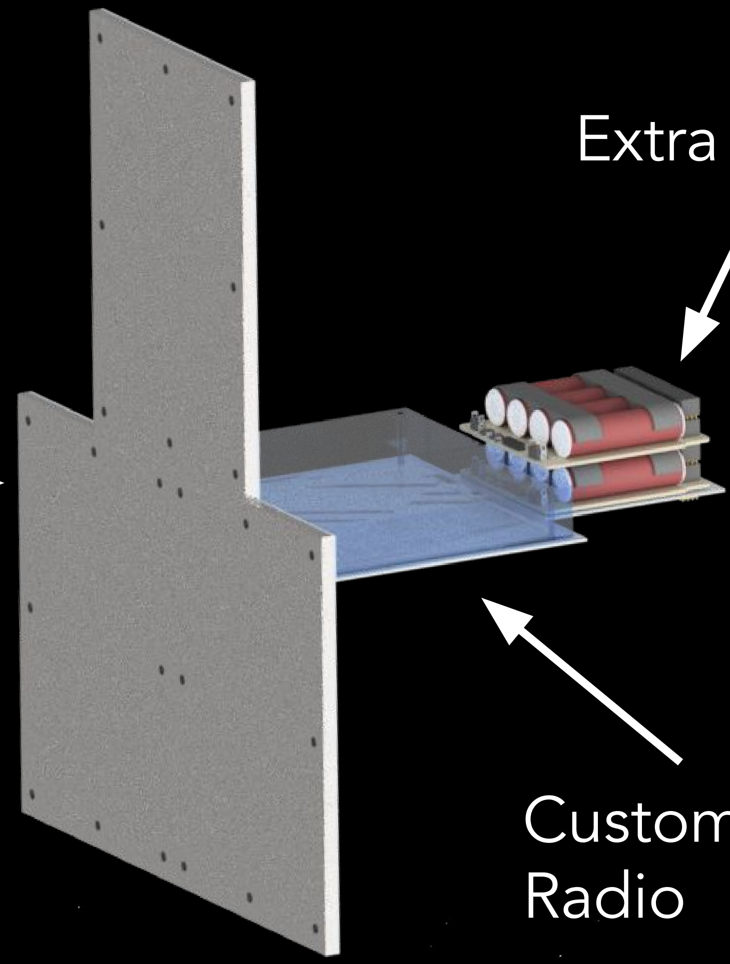
- Epiq Solutions Sidekiq M.2 SDR (6:2)
- Analog Devices 1:4 Power Multiplier (2)
- Analog Devices Amplifiers (3)
- Omnisemi 8:1 Output Multiplexer (1)
- Haigh-Farr Flexislot 7300 patch antenna (3)
- 2 extra battery packs





Repeater Payload

Configuration



Repeater Payload

Link Budget

Link Budget	Uplink: Ground to Satellite	Downlink: Satellite to Ground
Frequency	410.6 - 412.8 MHz	420.6 - 422.8 MHz
Data Rate	2400 bps	19200 bps
Receiver Gain	4 dB	-3 dB
Transmitter Gain	-3 dB	4 dB
Power (RF)	1 W	5 W
Margin	6.6 dB	4.3 dB

Subsystems and Budgets

ADCS

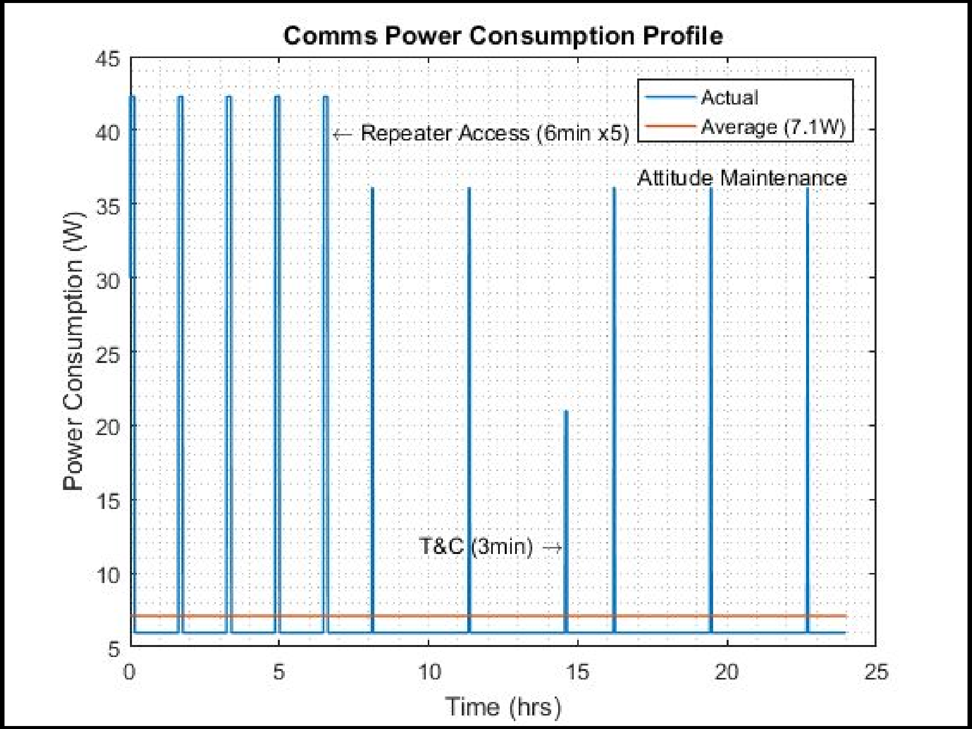
- Attitude knowledge requirement: 1 degree
- Fine knowledge required during TT&C and Sun-Tracking

	Repeater	Sun-Tracking
Pointing Requirement (deg)	21.7	10
Slew Rate (deg/s)	0.003	0.012

Subsystems and Budgets

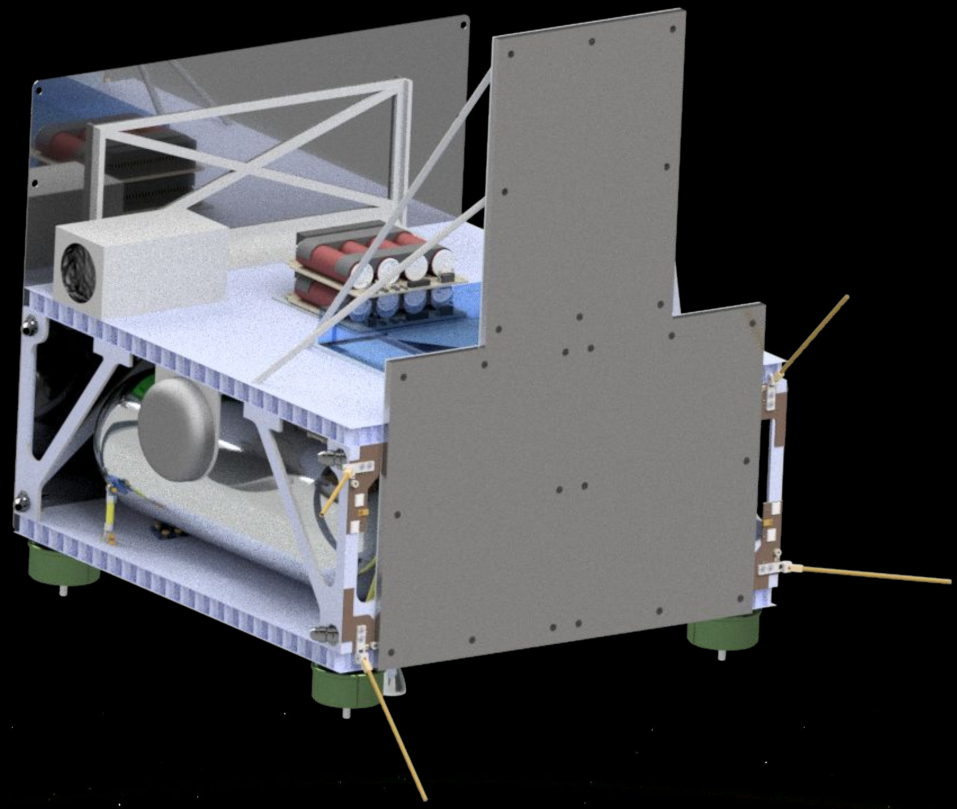
Power: Operations Cycle

Orbit	Operation	Net Battery Change (W-hr)
1-5	Repeater Access	-14.47
6-9	Power generation	+115
10	TT&C	-10.41
11-14	Power generation	+115
15 (partial)	Power generation & orbital maintenance	+30



Configuration

Payload and Bus



COMMON BUS

SECTION 6 OF 8

GRANT WEBSTER

Propulsion

Satellite Maneuvers Summary

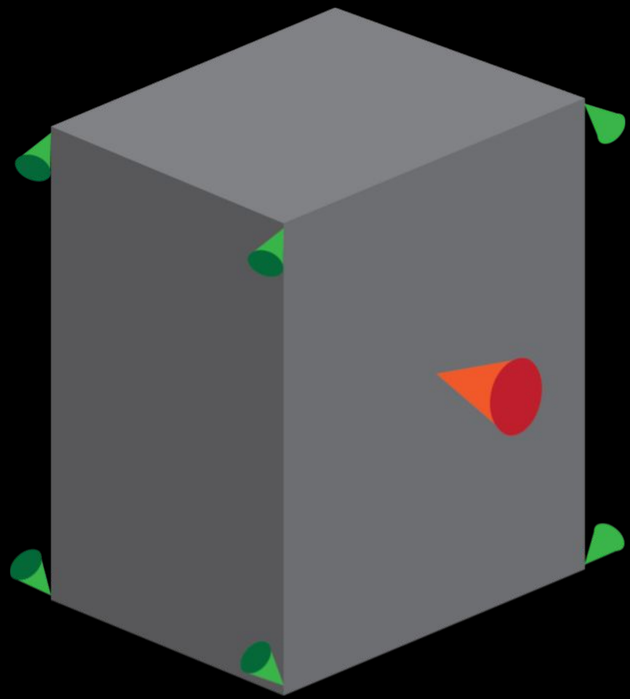
- 5 N High Performance Green Propellant Thruster
  - Propellant: LMP-103s

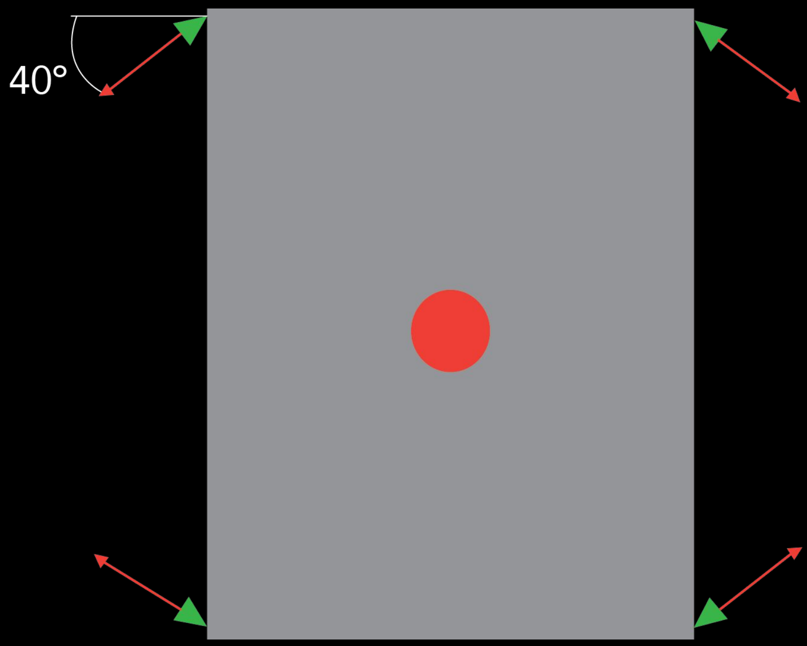
Maneuver	Injection Orbit Correction	Phasing	Stationkeeping	De-Orbit	Total
Imaging Required ΔV (m/s)	34	575	75	32	716
Comms Required ΔV (m/s)	1	132	0	48	181

Prop detail

ADCS

RCS Thruster Control





RCS Thrusters   Main Thruster

Communications

TT&C

- On-board system for TT&C:
  - UHF Band
  - Four whips in phase quadrature
  - BPSK modulation

TT&C Link Budget	Downlink	Uplink
Frequency	300 MHz	
Data Rate	9.6 kbit/s	
Gain of Receiver	14.7 dB	0 dB
Power (RF)	0.25 W	0.25 W
Margin	7.6 dB	

Power

Architecture

- 1 Body-mounted solar panel, sun tracking
- 1 x 40 W-hr battery pack for imaging satellites, 3 for communications satellites

Payload	Avg. Power (W)	Peak Power (W)	Energy Storage (W-hr)
Imaging	9.3	70.1	40
Comms	7.1	42.2	120

Power Baseline Assumptions

Thermal

Driving Components

Component	Operating Temperature (°C)	Heat Dissipation (W)	Operating Time (s)
Propellant	-5 to +50	~	~
Ku Horn Amplifier	-30 to +80	30	150
VIS/NIR Optical Payload	-10 to +50	28	200
Repeater Payload	-55 to +125	25.6	480
Thruster during Orbit Insertion	-50 to +50	135	900

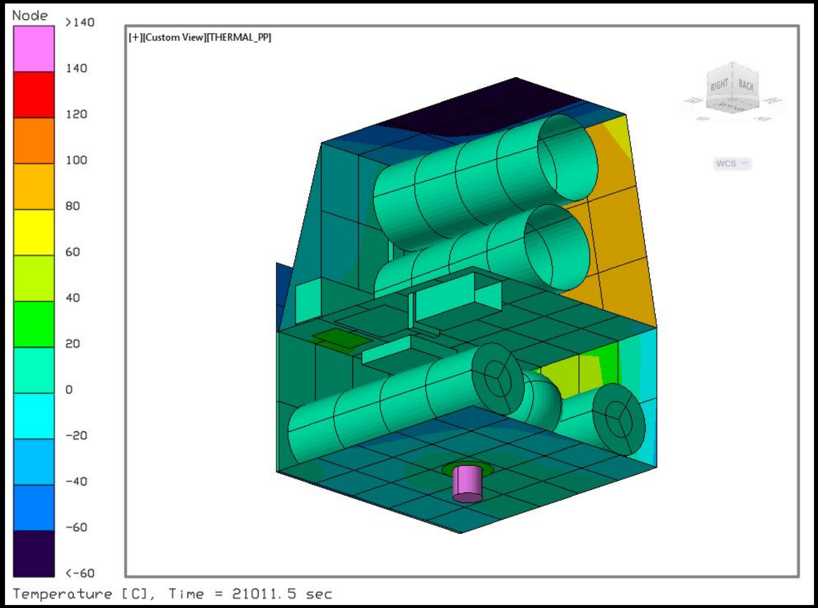
Thermal

Solutions

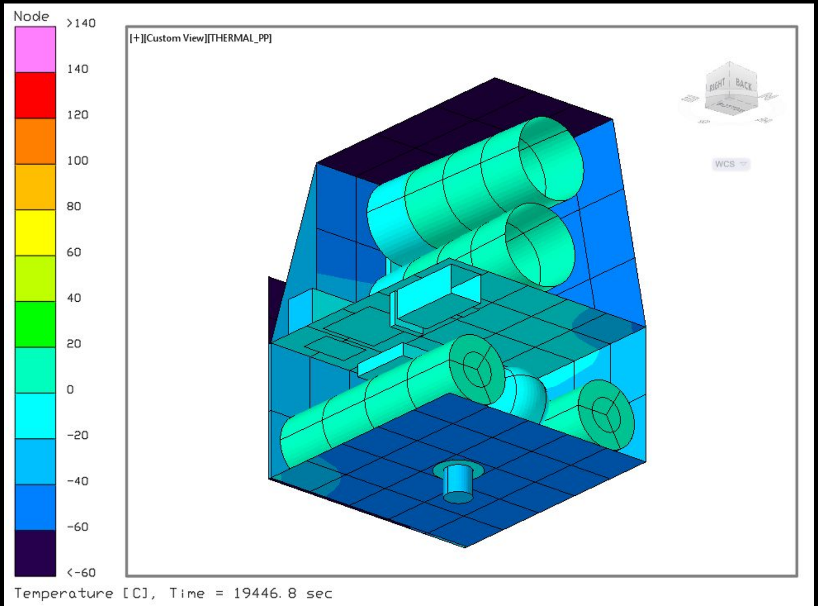
- Thermally isolate tanks and wrap with MLI
- PCM heat sink for Ku horn and Optical Payload
- High heat capacitance ceramic between thruster and bus
- MLI around Repeater Payload
- MLI around Optical Payload
- MLI around spacecraft bus

Thermal

Hot and Cold Cases - Imaging



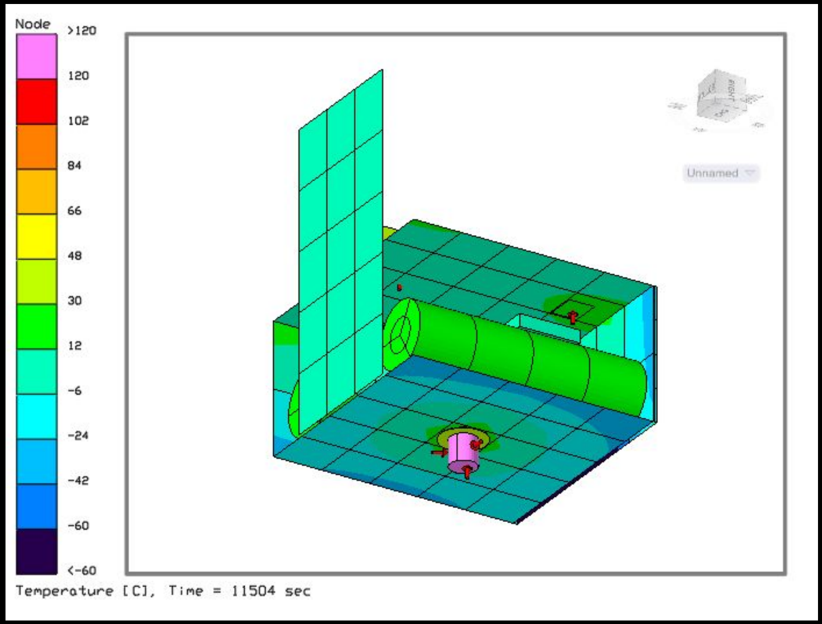
Hot Case: Polar Phasing Orbit



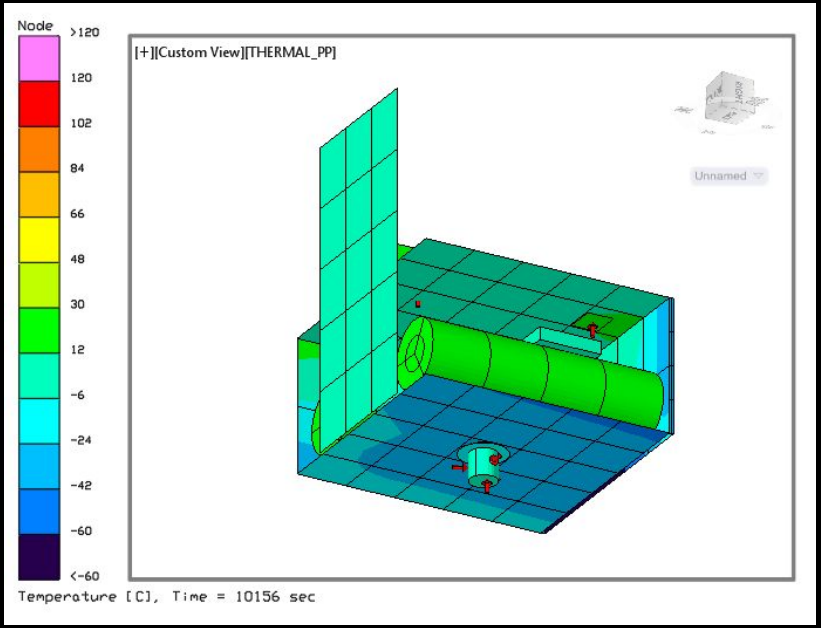
Cold Case: Sun-Synch Phasing Orbit

Thermal

Hot and Cold Case - Comms



Hot Case: Phasing Orbit



Cold Case: Phasing Orbit

Structures

Common Bus

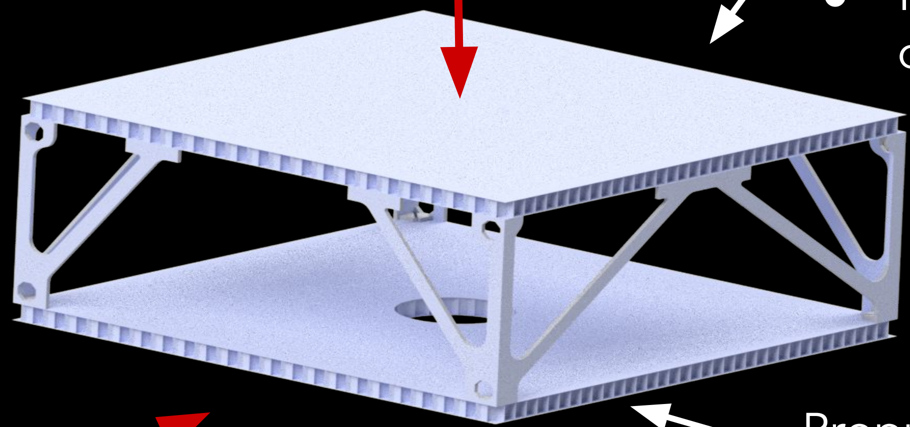
10.7g Axial Load

Payload Deck Panel:

- Identical to props deck

Corner Support:

- F.O.S = 2.5
- Al 6061
- 3 mm thk



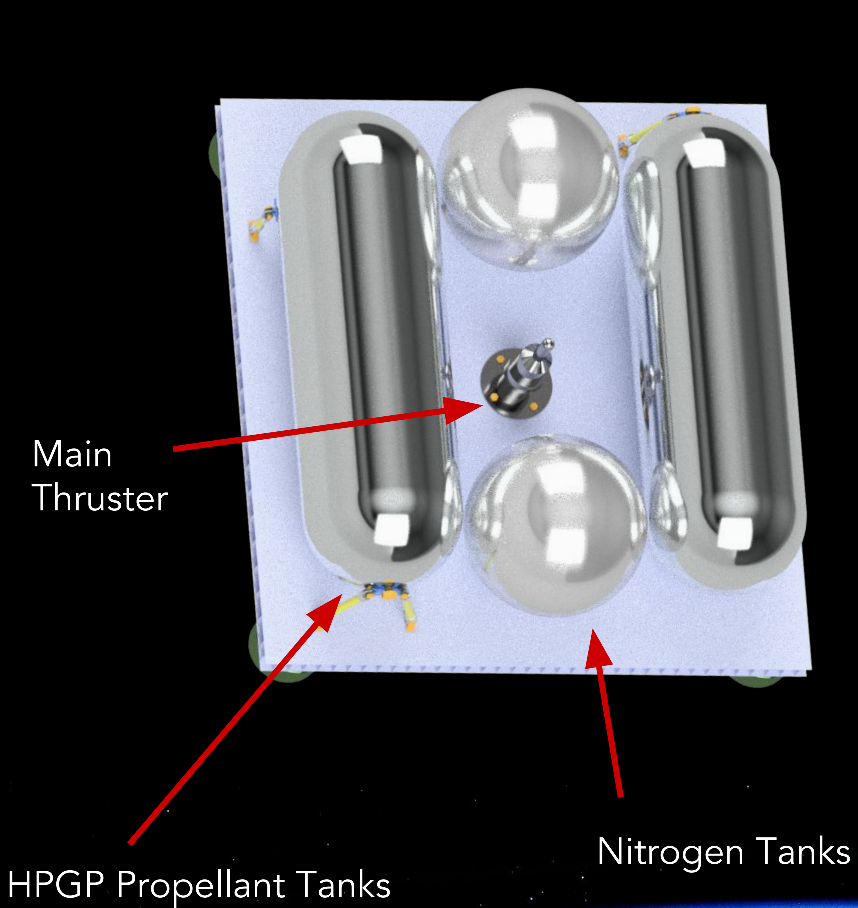
Propulsion Deck:

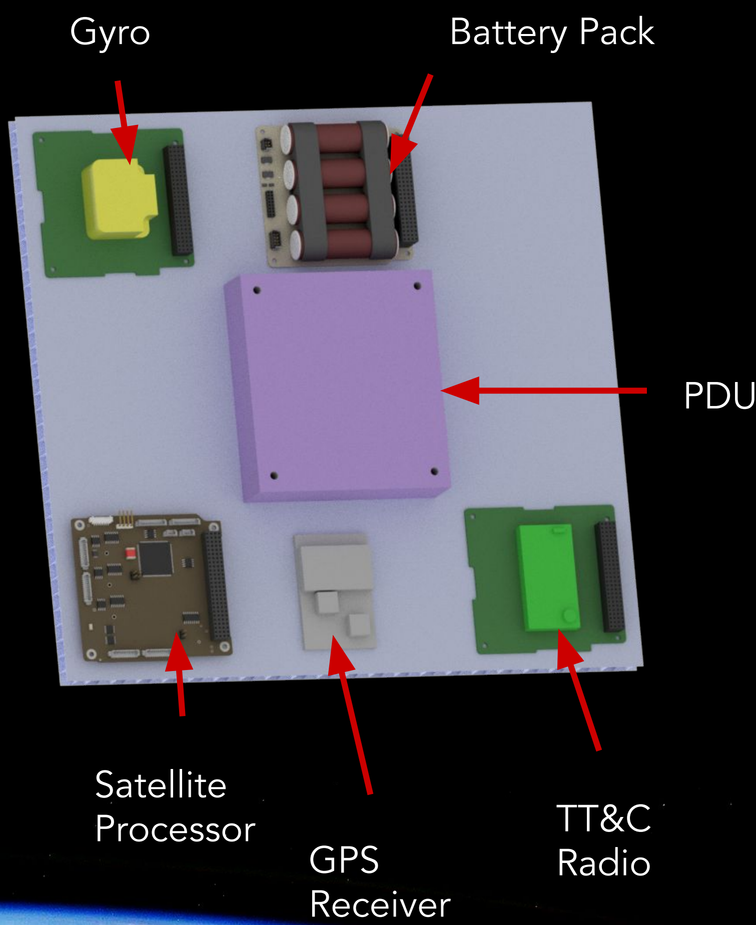
- F.O.S = 1.74
- Core: Al 5056
  - 9.5 mm thk
  - 4.2 pcf
- Facesheet: Al 2024
  - 0.25 mm thk

5g Lateral Load

Common Bus

Internal Components

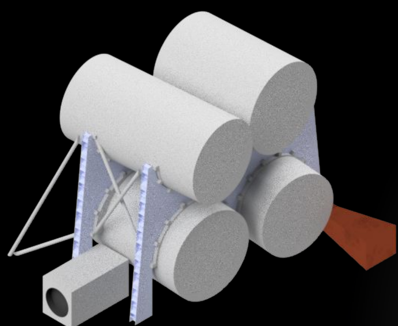




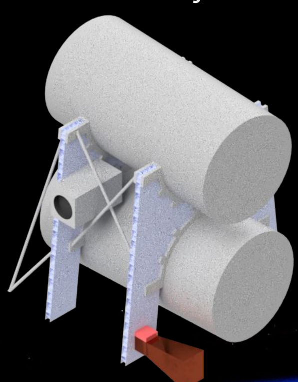
Common Bus

Interchangeable Payloads

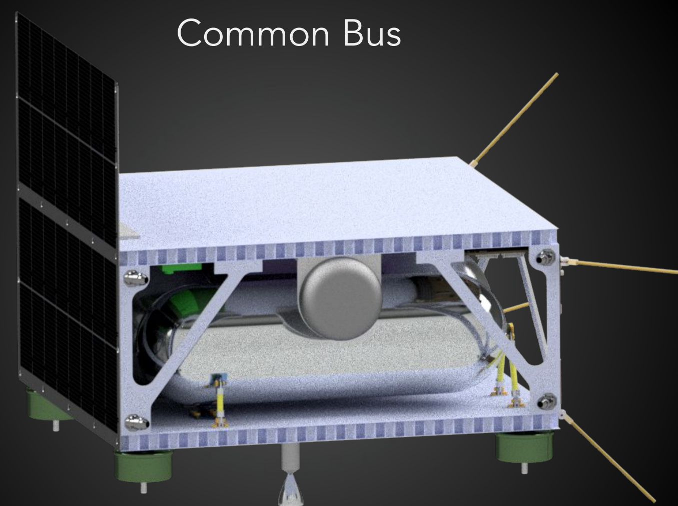
TIR Payload



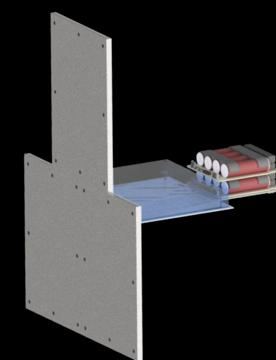
Vis/NIR Payload



Common Bus



Comms Payload



Common Bus

Mass Budget

Subsystem	Vis/NIR Mass (kg)	TIR Mass (kg)	Comms Mass (kg)
ADCS	1.26	1.26	1.26
Propulsion	10.86	10.86	4.0
Structure	2.89	2.89	2.89
Thermal	0.12	0.12	0.61
Payload	7.5	7.5	1.15
Comms	0.9	0.9	0.17
Power	1.57	1.57	2.07
Total	**25.1**	25.1	12.14

LAUNCH

SECTION 7 OF 8

ANTHONY NAHAL
AARON LEVIS
JAKE MARGULIES

System Requirements

- Time to launch
  - As quickly as possible from time of command to meet 12 hour and 24 hour payload requirements
- Storability
  - System must remain fully ready for 5 years
- Design
  - Driven primarily by the satellite requirements
- Versatility
  - Launch vehicle must be able to reach a range of target orbits

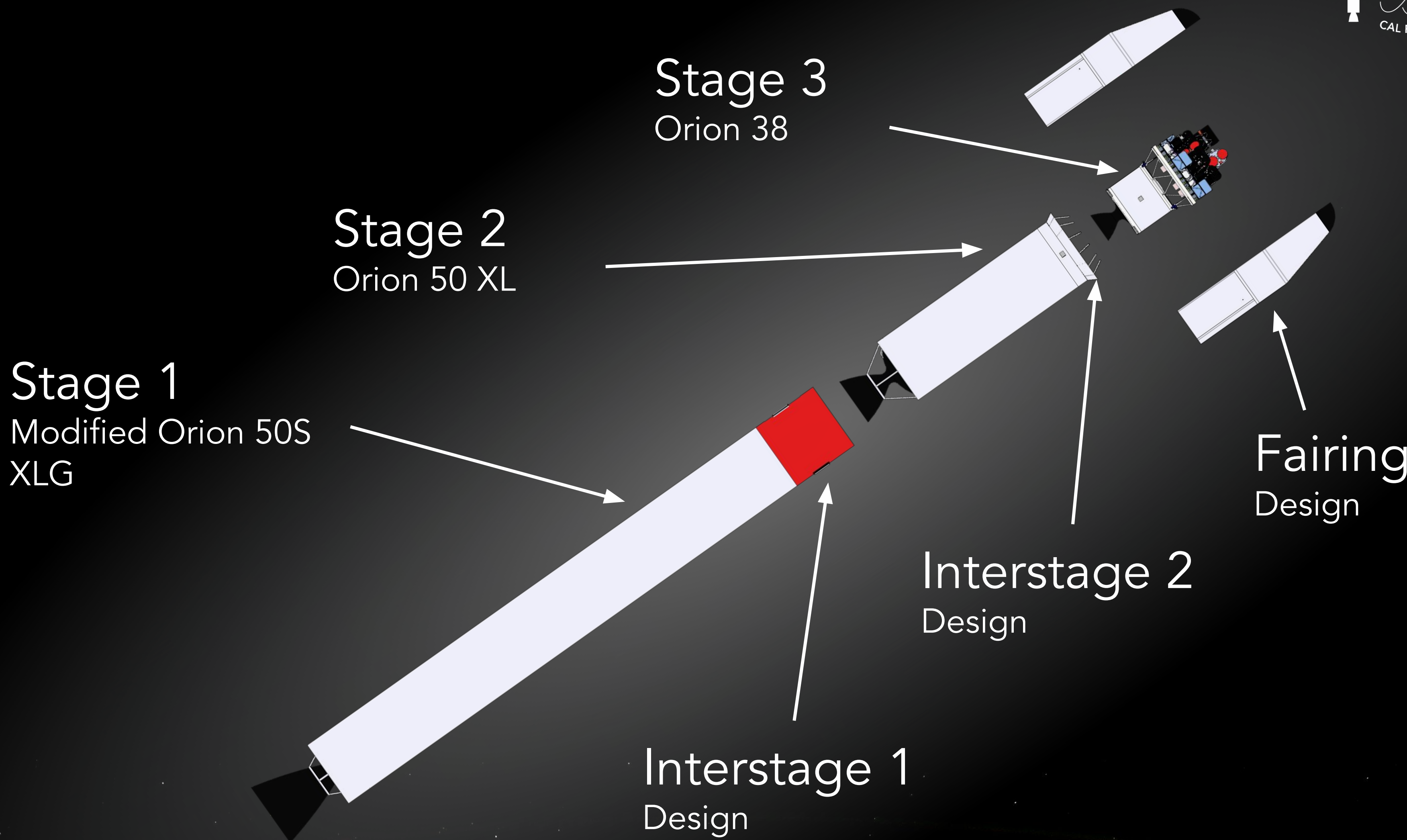
Major Trades

Trades	Status	Outcome
Launch Type: Air vs. Land vs. Sea	Closed	Launch from Land
Launch Sites: Build vs. Use Pre-existing	Closed	Build Launch Sites
Launch Vehicle: Design vs. Buy	Closed	Design Launch Vehicle
Storage Facility: Below vs. Above Ground	Closed	Above Ground
Propellant: Solid vs. Liquid	Closed	Solid

Launch Vehicle Overview

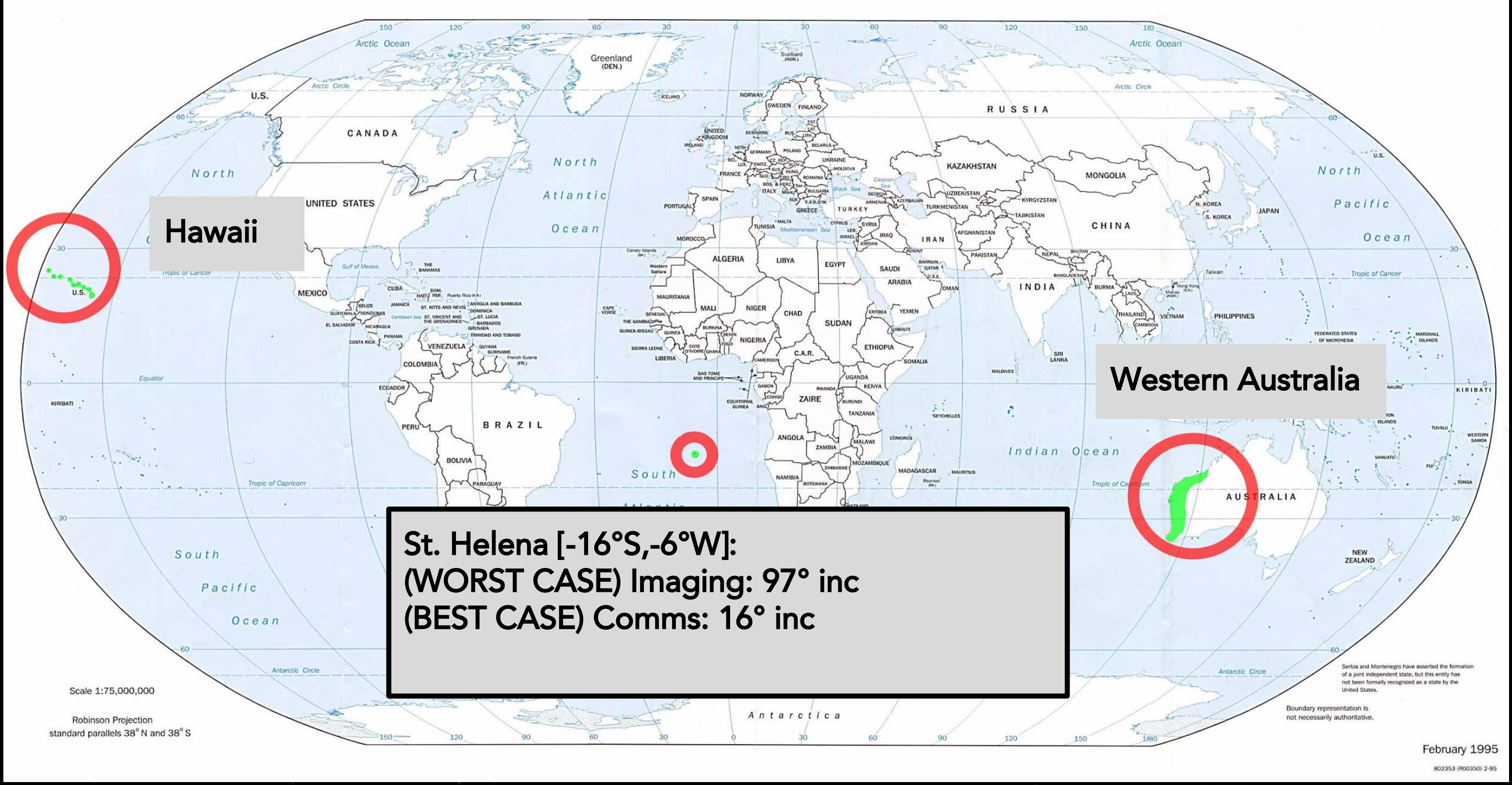
- 3 Stage
- Solid Propellant
- Sizing:
    - Total Height: 20.1 m
    - Rocket Diameter: 1.3 m
    - Fairing Diameter: 1.5 m
    - Total Mass: 24,550 kg

Launch Vehicle Overview

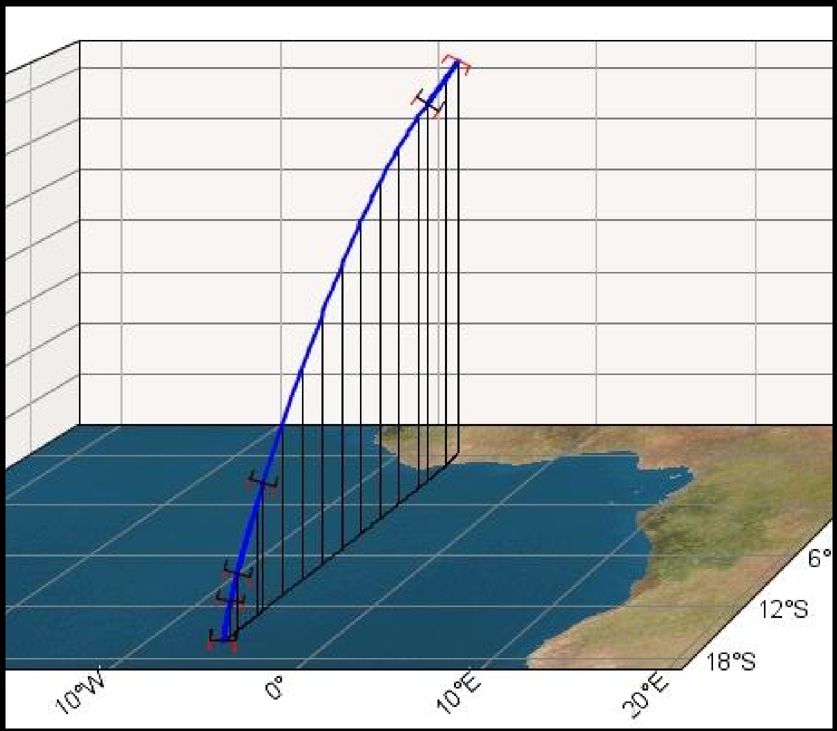


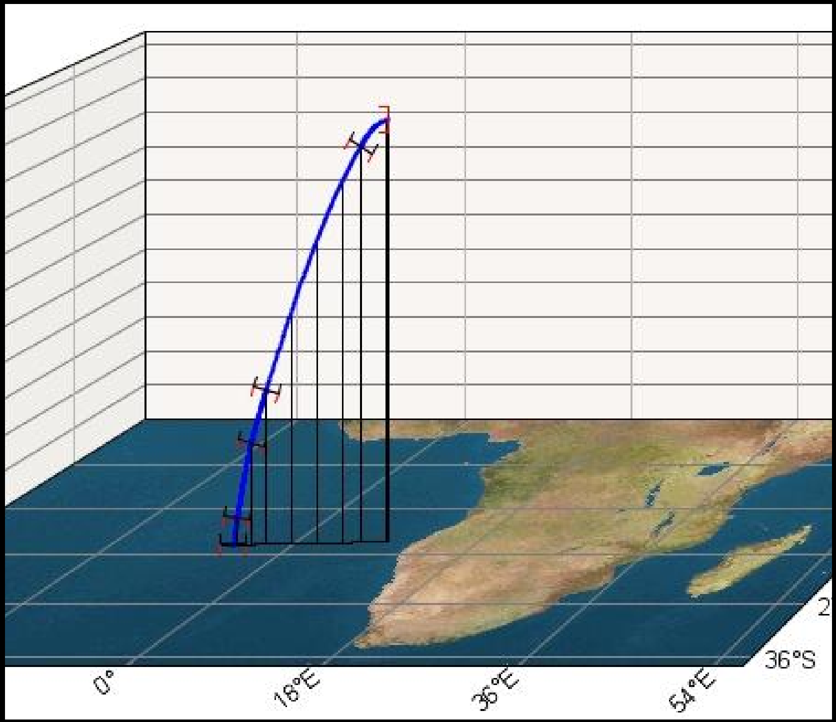
Launch Vehicle Overview

Launch Sites



Trajectory





Worst Case: 97.2 kg Imaging Package, 567 x 3167 km, 97.7° inclination

Best Case: 43.6 kg Comms Package, 625 x 1139 km, 15.95° inclination

Trajectory

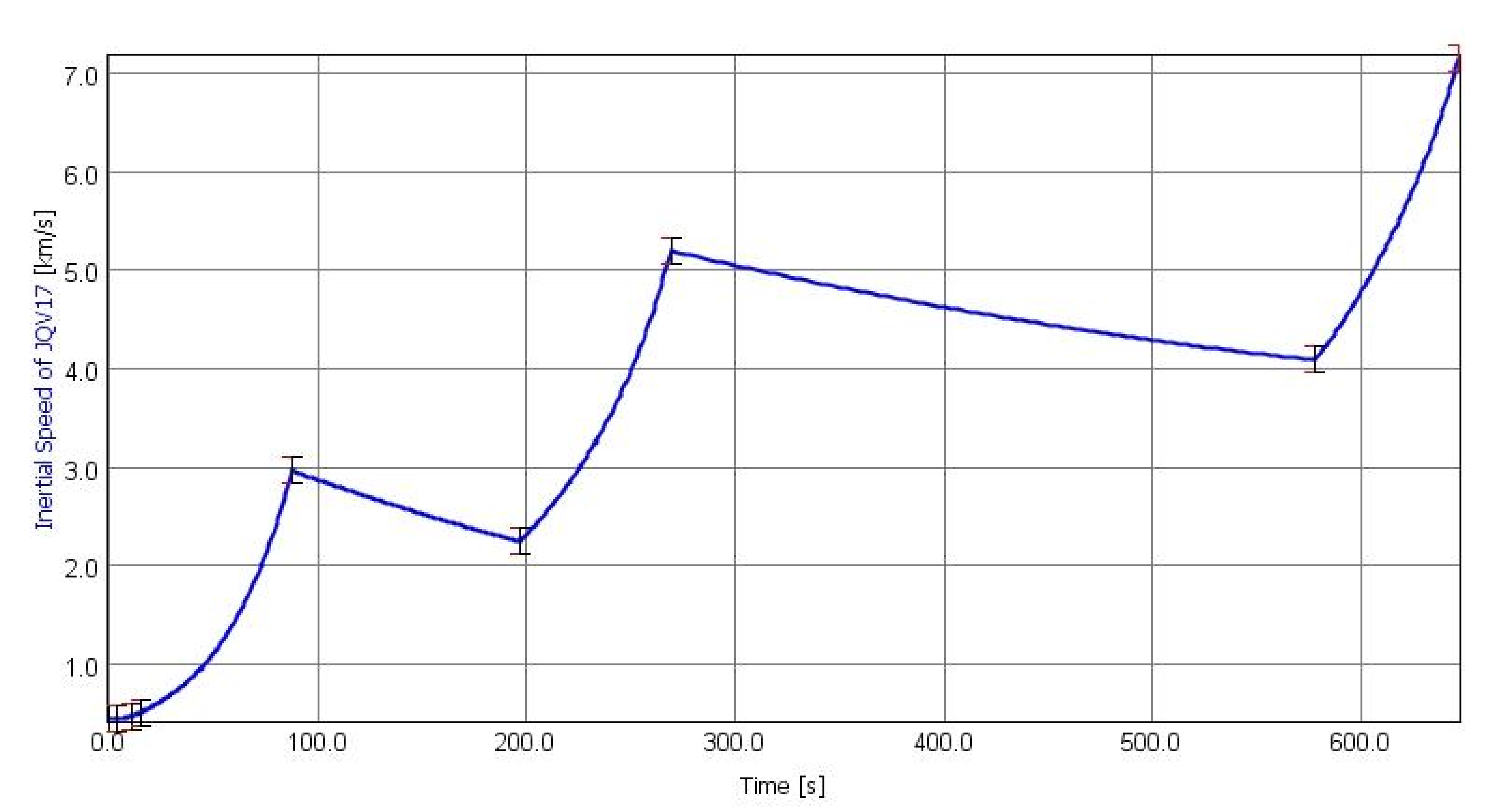
Timeline (Best Case Scenario)

Event	Time Event Starts	Altitude (km)
Liftoff / S1 Start	T+0:00	0.03
Max Dynamic Pressure	T+0:45	20.0
S1 Cutoff / Coast 1 Start	T+1:27	70.2
S2 Start / Hot Separation	T+3:16	271.2
S2 Cutoff / Fairing Deploy	T+4:29	414.5
S2 Separation / Coast 2 Start	T+4:29	414.5
S3 Start	T+9:38	1066.5
S3 Cutoff	T+10:46	1136.5

Trajectory

Best Case Velocity Bleed

- 43.6 kg Comms Package, 625 x 1139 km, 15.95 degree inclination



Staging

Overview

- All stages use HTPB polymer, 19% aluminum
- Solid motors were selected due to:
  - Long term storage capabilities
  - Simplicity of design integration
  - Performance metrics

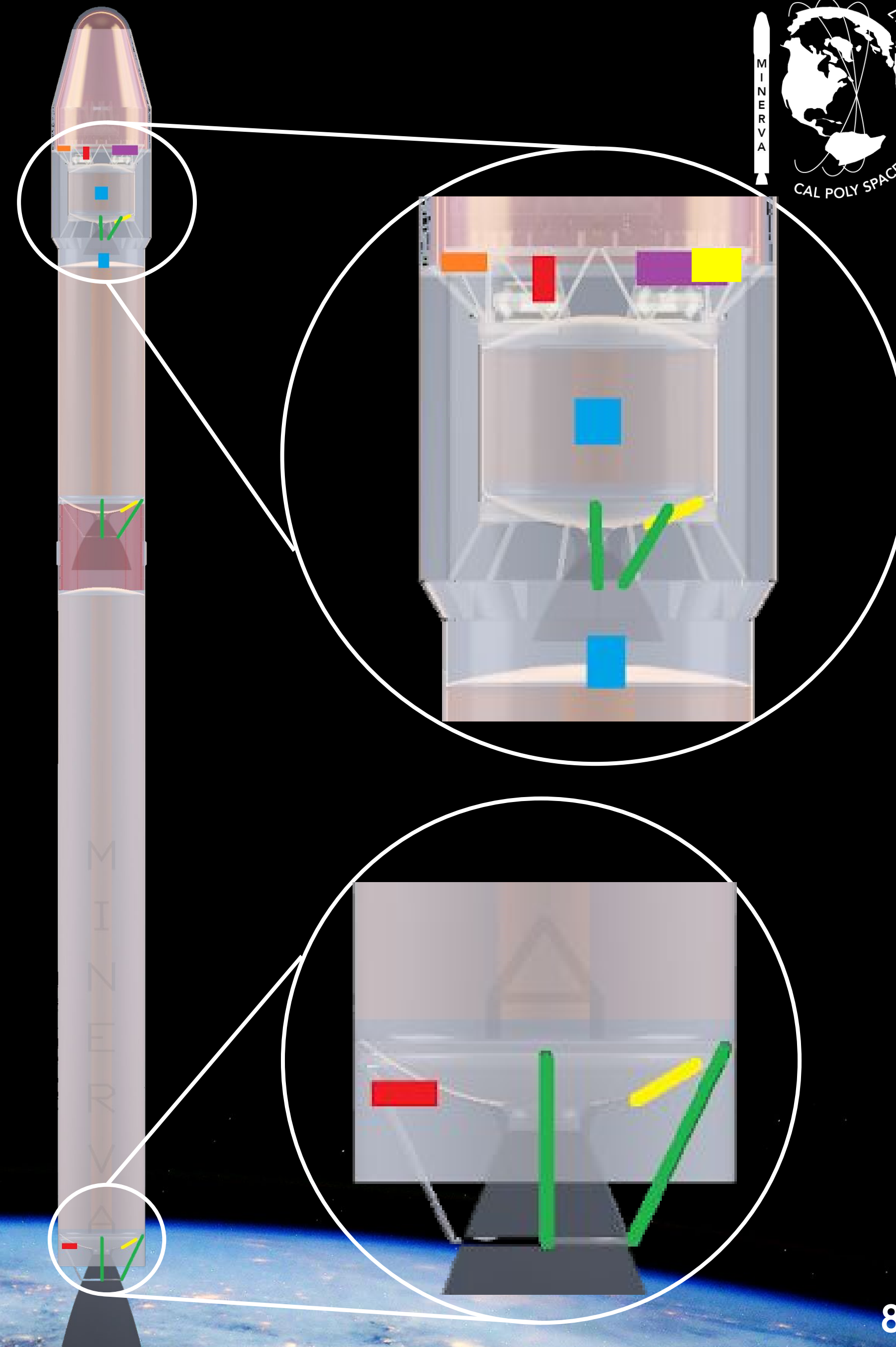
Stage	Engine	Wet Mass (kg)	Max. Thrust (kN)	Burn Time (s)
1	Orion 50S XLG	18,814	588	87.5
2	Orion 50 XL	4,537	160	72.5
3	Orion 38	1,139	32.2	68.5

Subsystems

GN&C

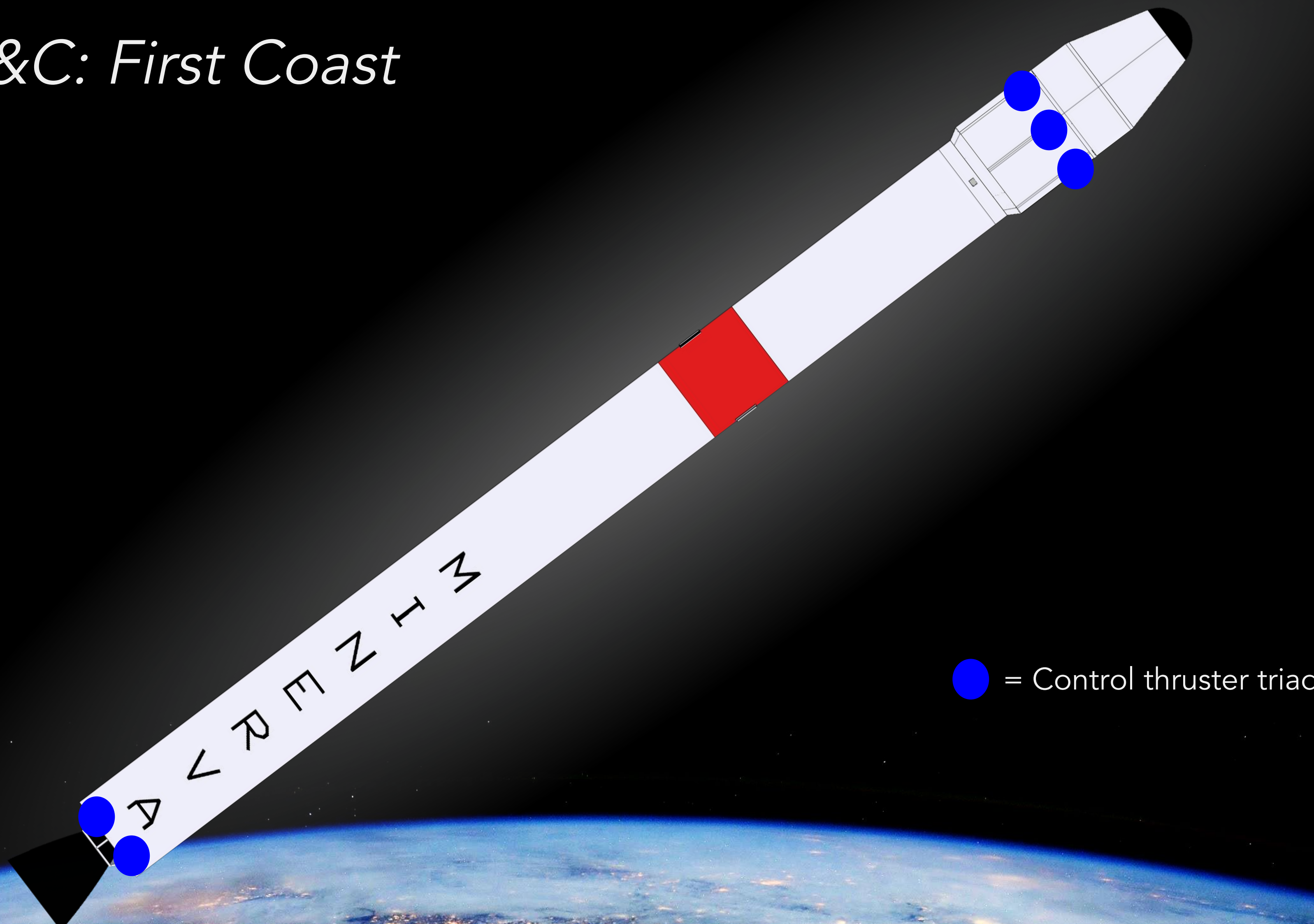
RED - IMU
PURPLE - Flight Computers
YELLOW - Flight Termination
BLUE - Patch Antennas
ORANGE - GPS
GREEN - Gimbal Actuation

Phase	Control
Stage Burns	Gimbal Actuation
Coasting	Cold Gas Thrusters



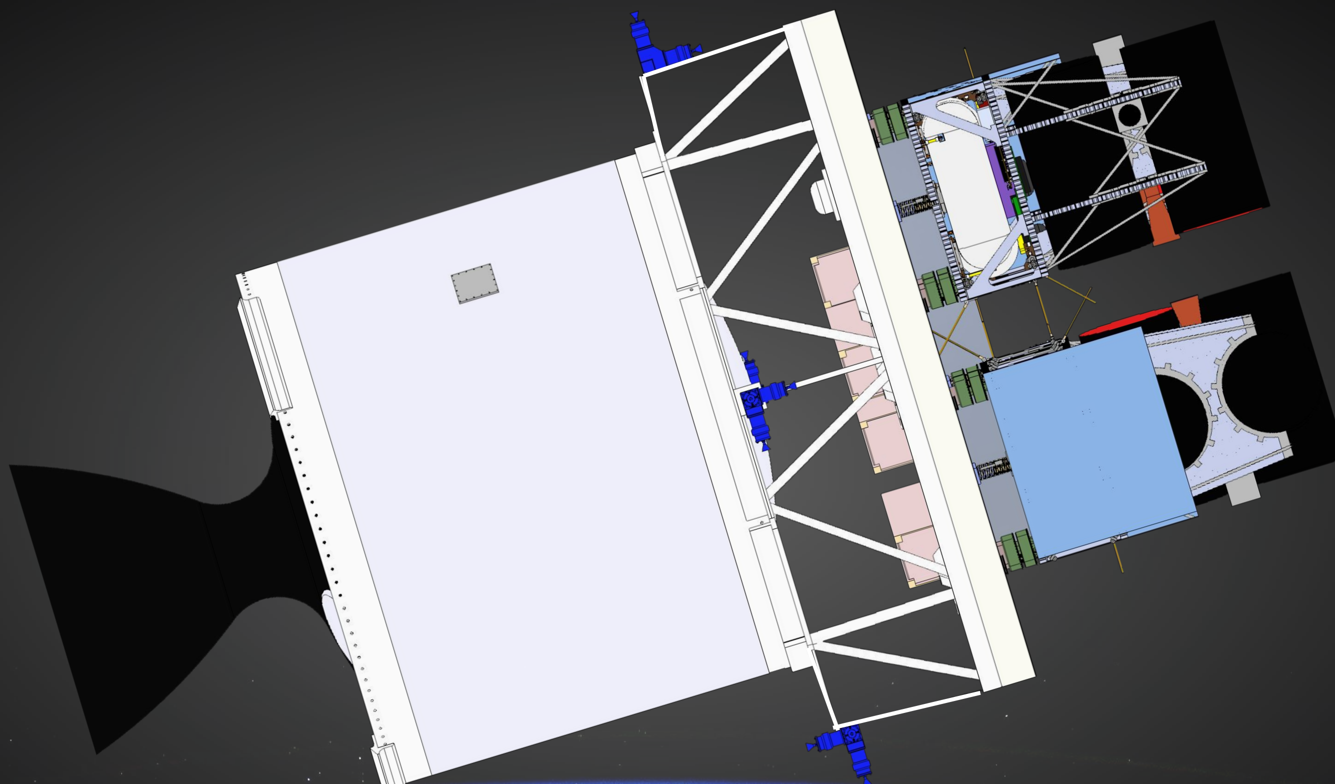
Subsystems

GN&C: First Coast



Subsystems

GN&C: Second Coast & Payload Deployment



Subsystems

Power: Budget

- 3 Space Vector Lithium-Ion Cells: 168 Watt-Hour capacity total
- Gimbal Systems powered by thermal battery provided by Orbital ATK

	Component	Quantity	Watt-Hour
Stage 1,2,3 Motors	Igniter	3	7.00E-04
Interstages	Separation Bolts	12	9.00E-04
Forward Equipment Bay	Computer	3	2.52
	IMU	2	5.25
	Radio	1	3.36
	Autonomous Flight Termination System	1	11.76
	Cold Gas Thrusters	16	116.72
	GPS	1	5.38E-02
Payload Area	Payload Separation System	16	1.70E-03
Total Watt-Hours Required			142
Watt-Hours Supplied			168

Subsystems

Telemetry

- Omni-slot Patch
    - 6 dB peak gain
    - 4 Antennas
    - Omnidirectional
- No downrange ground stations
    - Communication with launch site only

Link Budget	Downlink
Frequency	300 MHz
Data Rate	9600 bps
Satellite Gain	6 dB
Ground Gain	12 dB
Power (RF)	1 W
Margin	10 dB

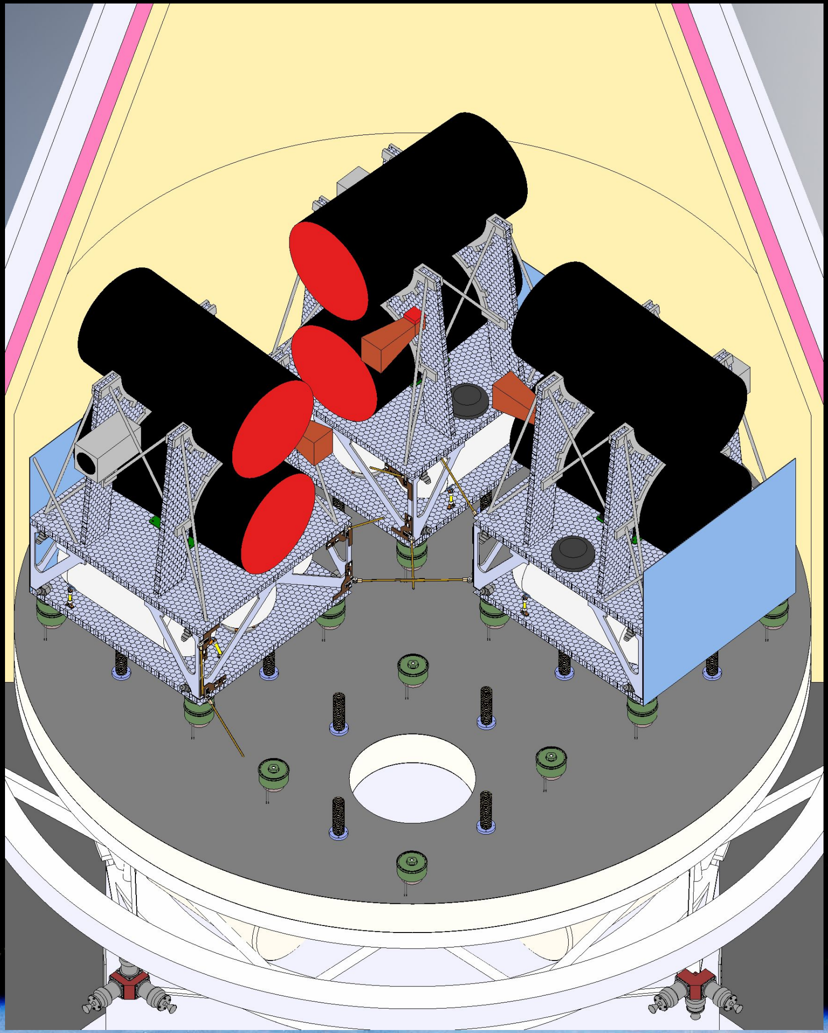
Payload Integration

Major Trades

Trade	Status	Outcome
Satellite Mounting: Axial vs. Radial	Closed	Axial
Payload Release: Pyros vs. Actuators	Closed	Split-Spool Actuators
Payload Eject: Springs vs. Thrusters	Closed	Springs

Spring
Radial

Payload Integration



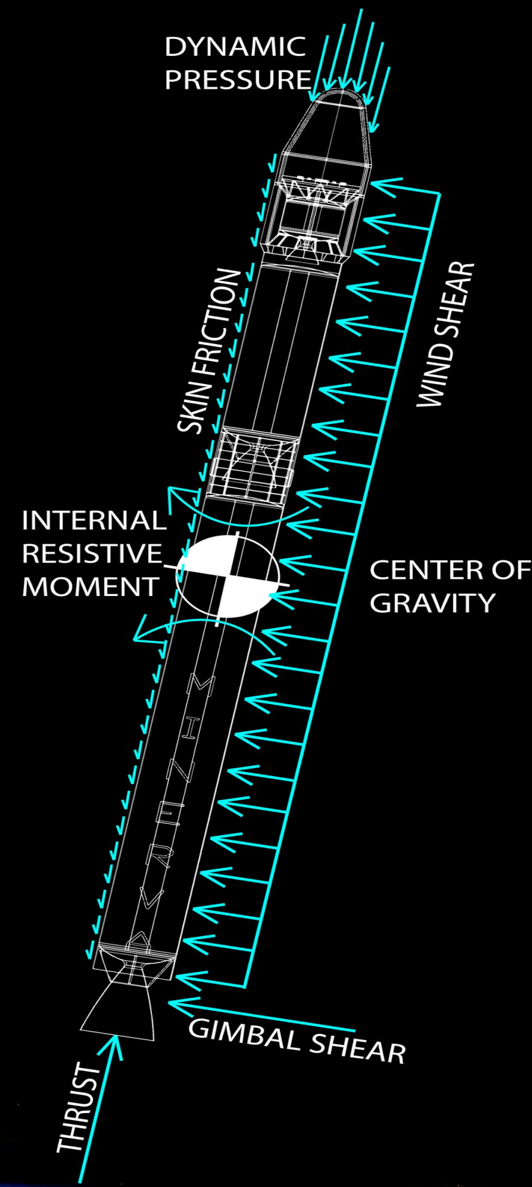
Payload Integration

- Mounting Plate: Honeycomb panel
  - Mass Estimate: 9.1 kg
- Residual Velocities:
  - Translational: 22 (+/-2) cm/s
  - Rotational: <1.5 deg/s
- Release: NEA 9200 Split-Spool
  - Peak Shock: <300 g's
  - Release Time: <10 ms
- Damper: MOOG ShockWave Isolator
  - Shock and load attenuation

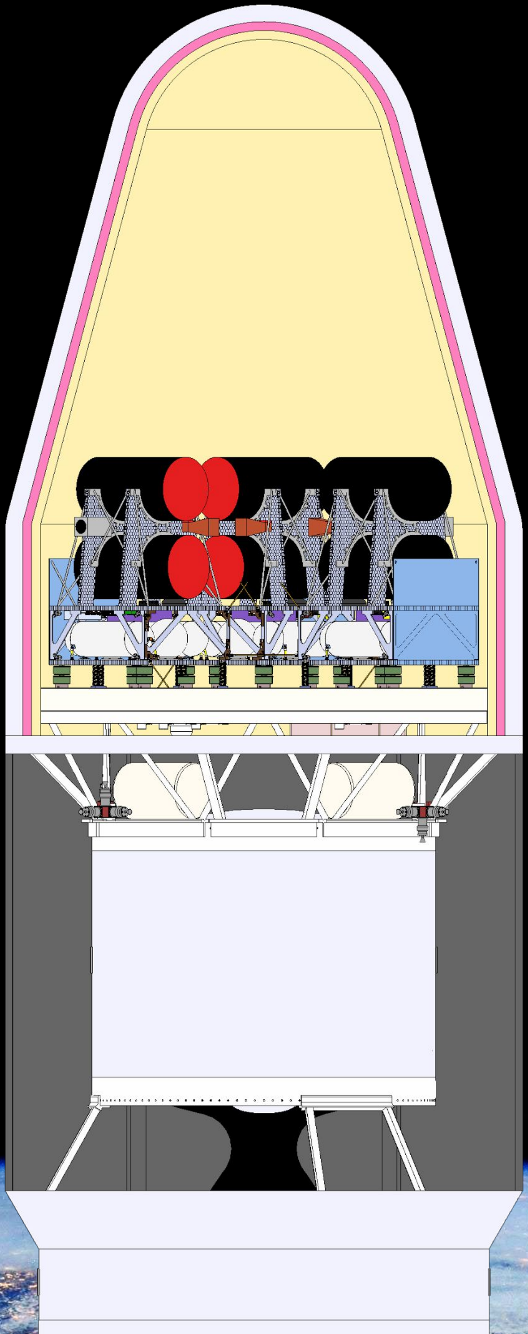
Structures

Launch Vehicle Structural Requirements

- Max Accelerations/Loads
  - Axial: 668 kN (@10.7g)
  - Lateral: 58 kN
  - Dynamic Pressure: 80 kPa
  - Drag: 85 kN



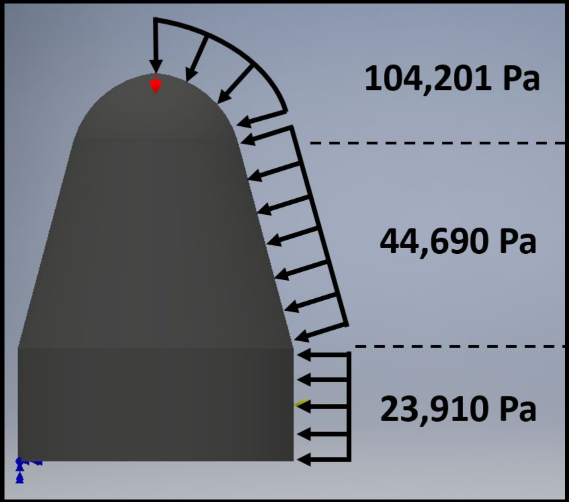
Structures

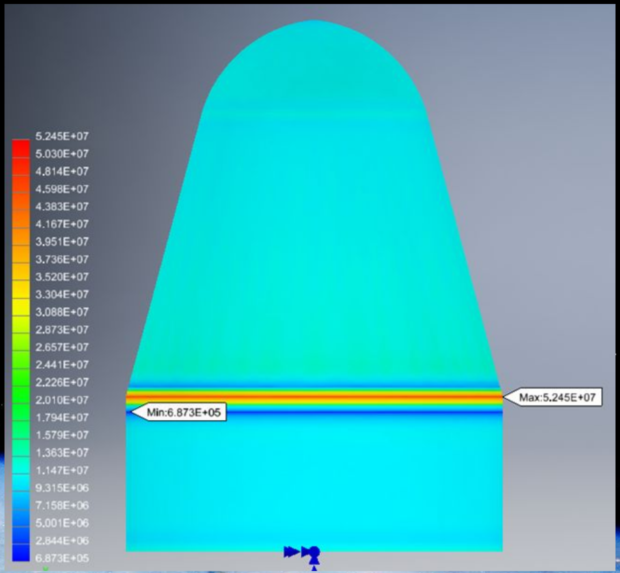


Structures

Fairing Analysis

Parameter	Value
Material	CFRP
Wall Thickness	2.2 mm
Mass	24.7 kg
Analysis Type	Linear Static & Buckling
Buckling Load	1.2x Load Case
Max Stress	52.5 MPa
Max Displacement	0.15 mm
Min Factor of Safety	10.9





Thermal

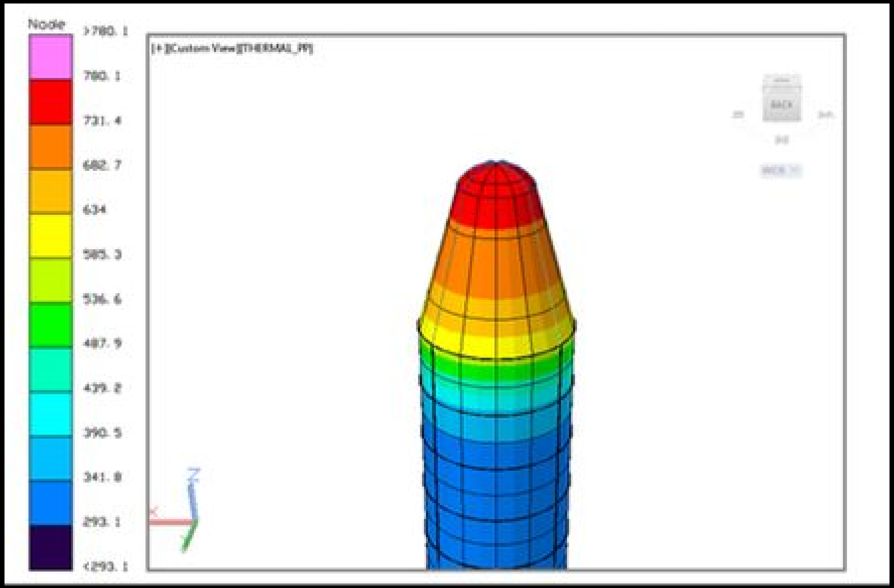
Component Considerations

- Thermal isolation from engines
- Launch trajectory aeroheating
- Ablation, Earth IR, Albedo

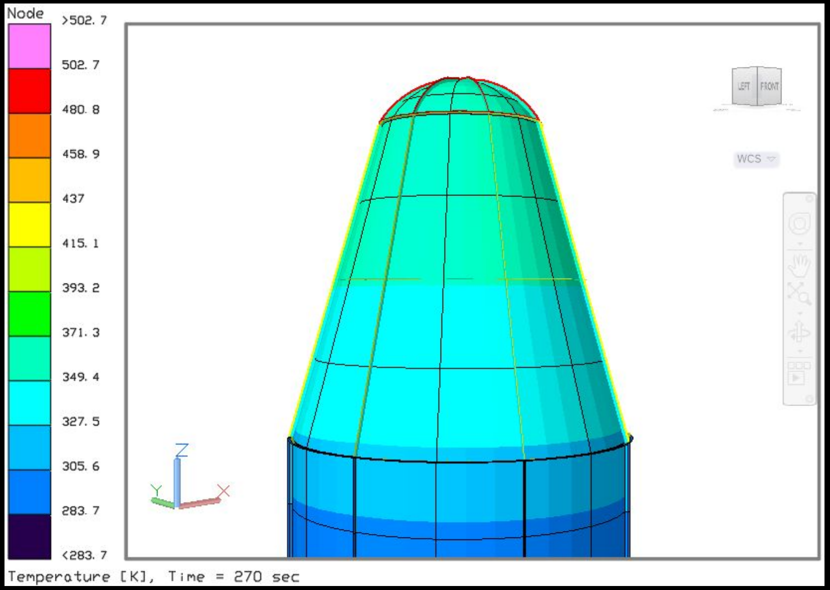
Section in LV	Component	Temperature Range (°C)
Interstage 1/2	Flight Termination Charge	-54 to 71
Stage 3	Radio	-30 to 85
Forward Equipment Bay	Computer	0 to 70
	Lithium Ion Batteries	-20 to 70
	GPS Receiver	-49 to 50
Payload	Imaging/Comm Satellite	10 to 50

Thermal

Fairing Analysis



Thermal Contour - No Insulation



Thermal Contour - With Insulation

Max Heat Flux (W/m^2)	Max Temp No Insulation (°C)	Max Temp with Insulation (°C)	Observed Payload Temp (°C)
60,000	627	95	20

Mass Budget

Stage	Component	Mass (kg)	Total Mass (kg)
1	Propellant	17233	18815
	Dry	1582	
2	Propellant	3915	4537
	Dry	622	
3	Propellant	770	964
	Dry	194	
3+	Forward Equipment Bay	59	234
	Fairing	75	
	Payload	100	
TOTAL			24550

GROUND

SECTION 8 OF 8

ANDREW KLEVE
DAVID GILLESPIE

System Requirements

- Enable the launch vehicles satisfy 12hr/25% and 24hr/100% system requirements for any location in the world
- Provide reliable 5 year storage support
- Provide in-flight launch vehicle communication and launch abort support
- Enable images to be downlinked rapidly after satellites pass over the target area

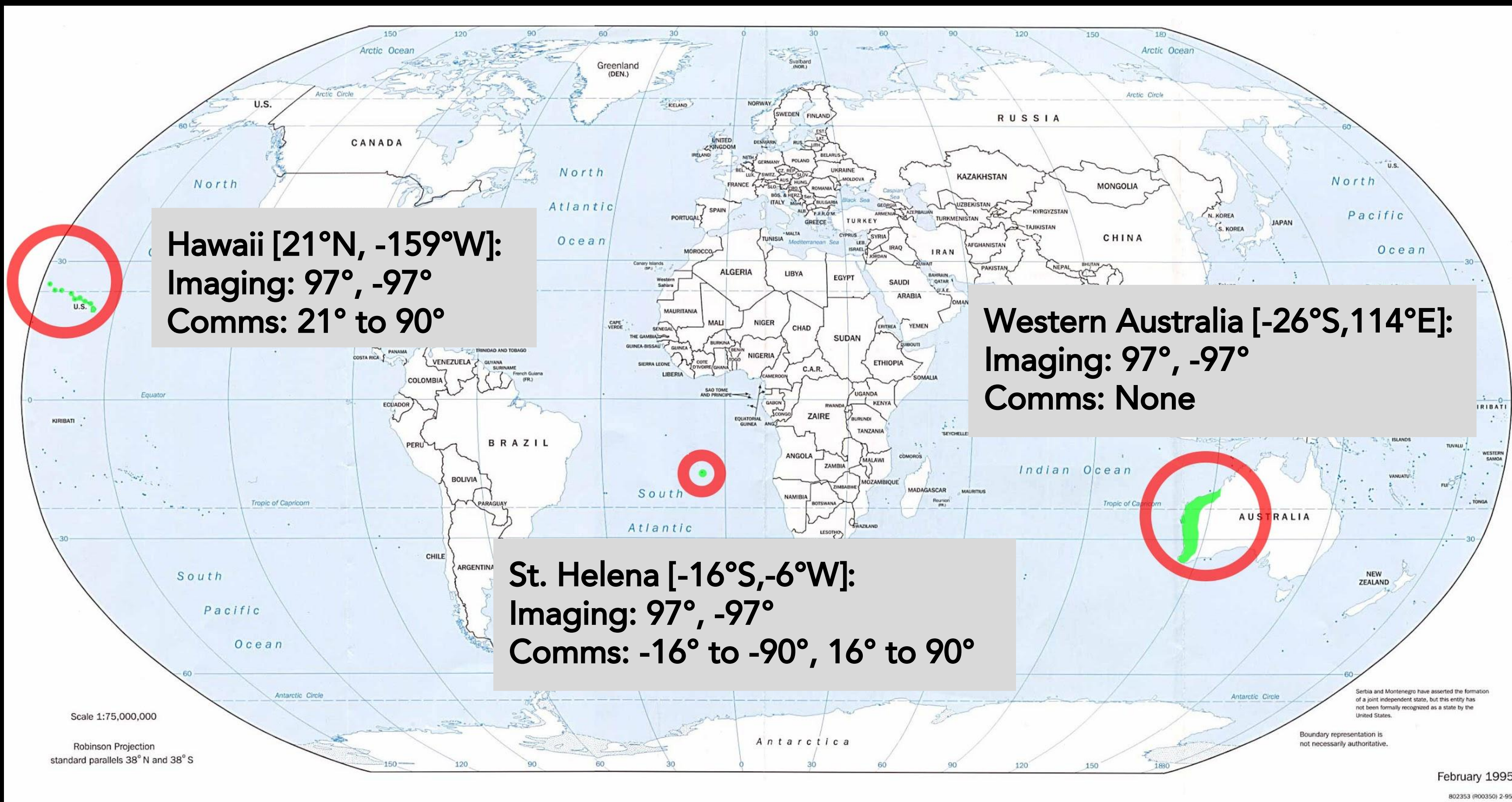
Launch Sites

Launch Locations Evaluated by:

- Launch azimuths to meet required orbit inclinations
- Political stability (evaluated with fragility index)
- Range safety
- Risk of natural disaster occurring at launch site
- Weather

Launch Sites

Launch Site Selection



Hawaii [21°N, -159°W]:
Imaging: 97°, -97°
Comms: 21° to 90°

Western Australia [-26°S,114°E]:
Imaging: 97°, -97°
Comms: None

St. Helena [-16°S,-6°W]:
Imaging: 97°, -97°
Comms: -16° to -90°, 16° to 90°

Map of all launch sites considered

Launch Sites

Launch Pad Distribution

- 17 total launch pads distributed amongst 5 major launch sites.
- 11 successful vehicles (6 are redundant) are required to provide full coverage.

	Imaging	Comms
Hawaii (Oahu, Kauai)	3	1
St. Helena (West and East sides of the island)	2	5
Western Australia	6	--

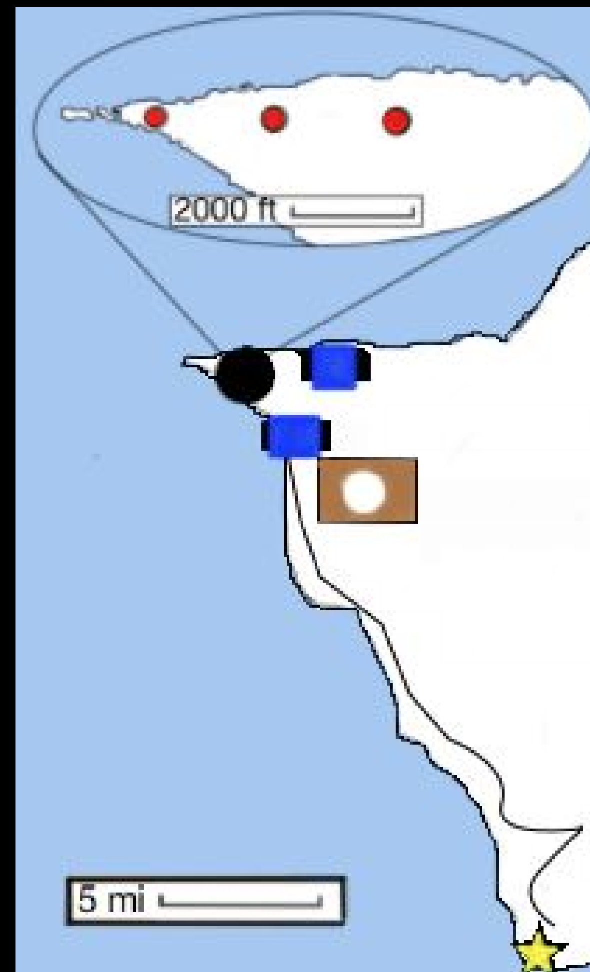
Launch Sites

Hawaii Launch Range

Launch Sites

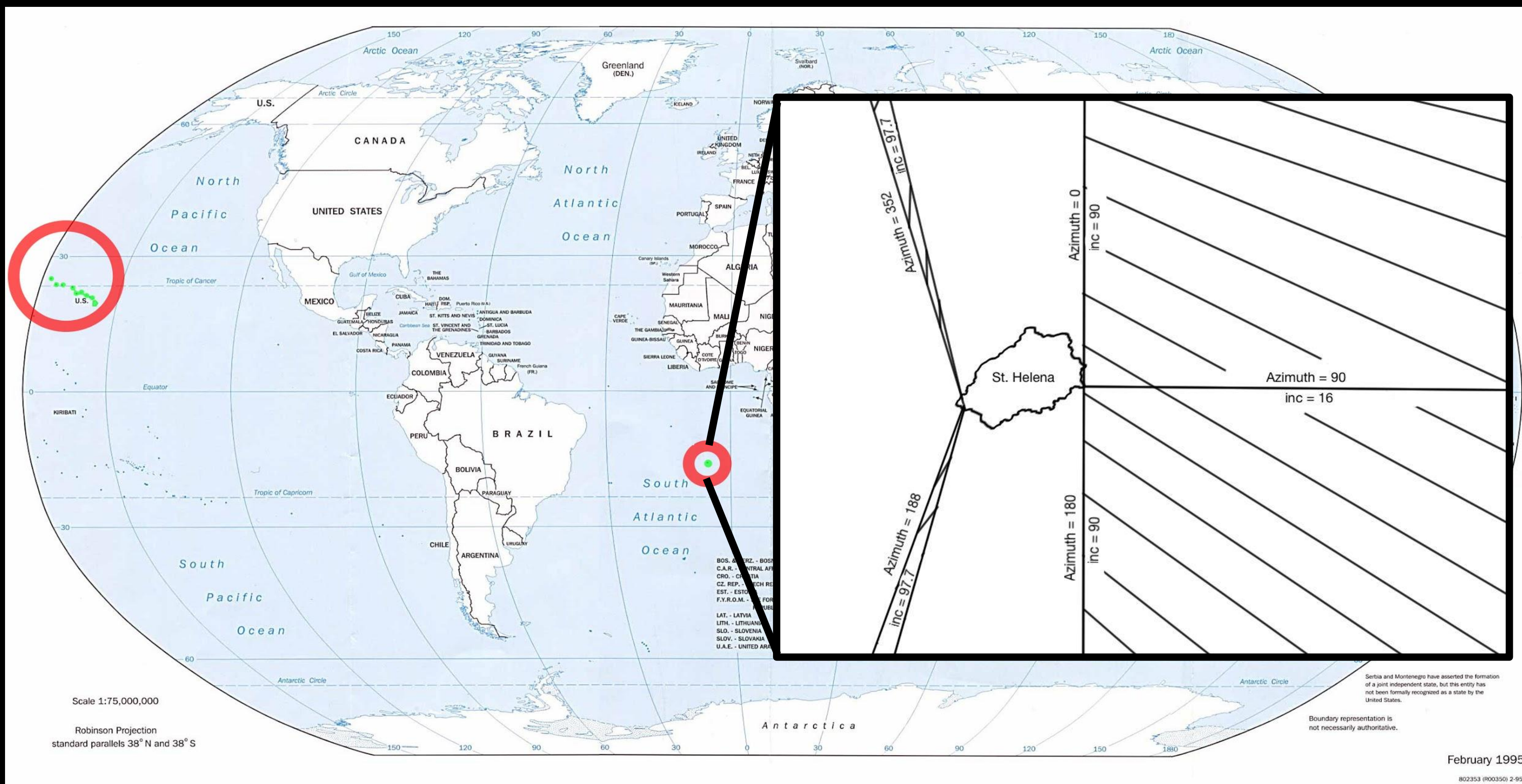
O'ahu Site Map

Legend	
Symbol	Meaning
	Shipping Port
	Command & Processing
	Roadway
	Launch Pad
	Ground Antenna



Launch Sites

St. Helena Launch Range

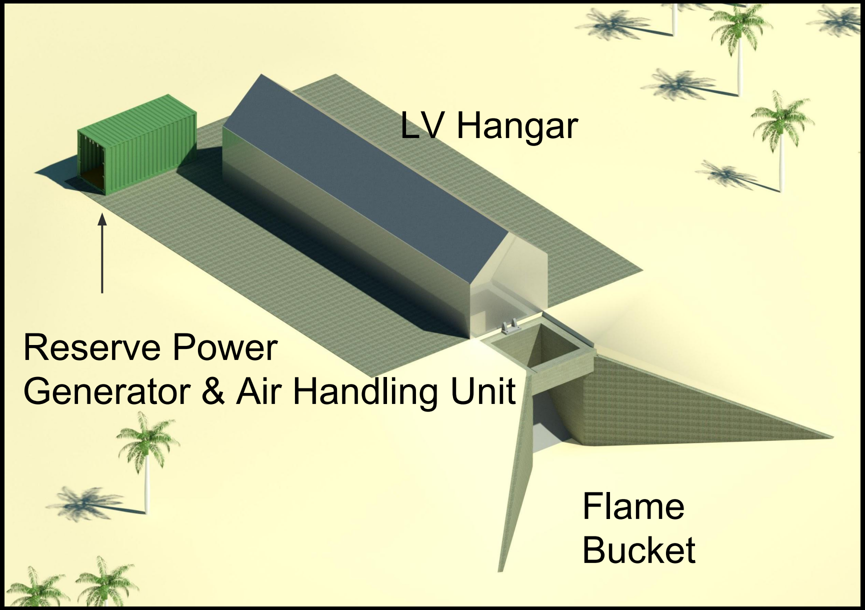


Launch Sites

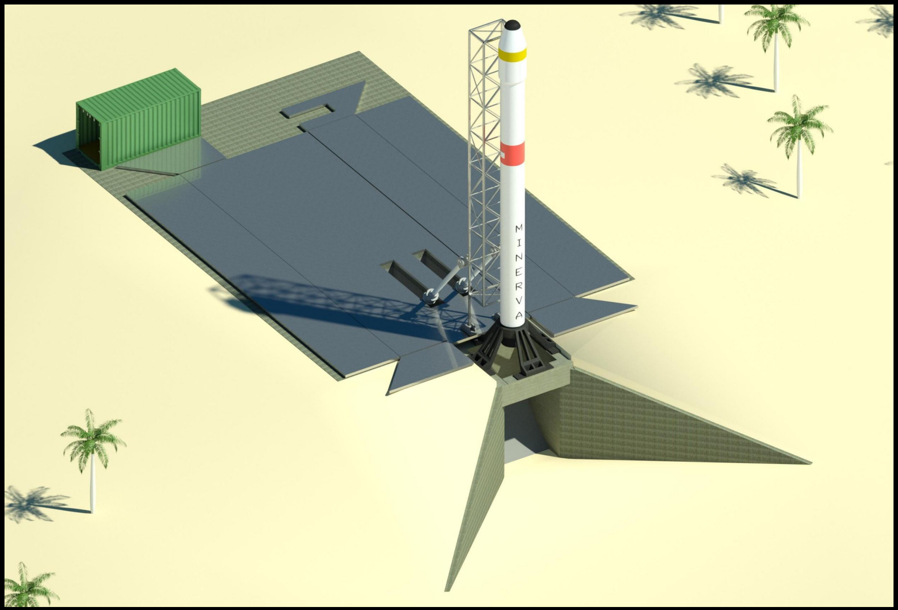
Australia Launch Range

Launch Sites

Ground Infrastructure



Stored Position



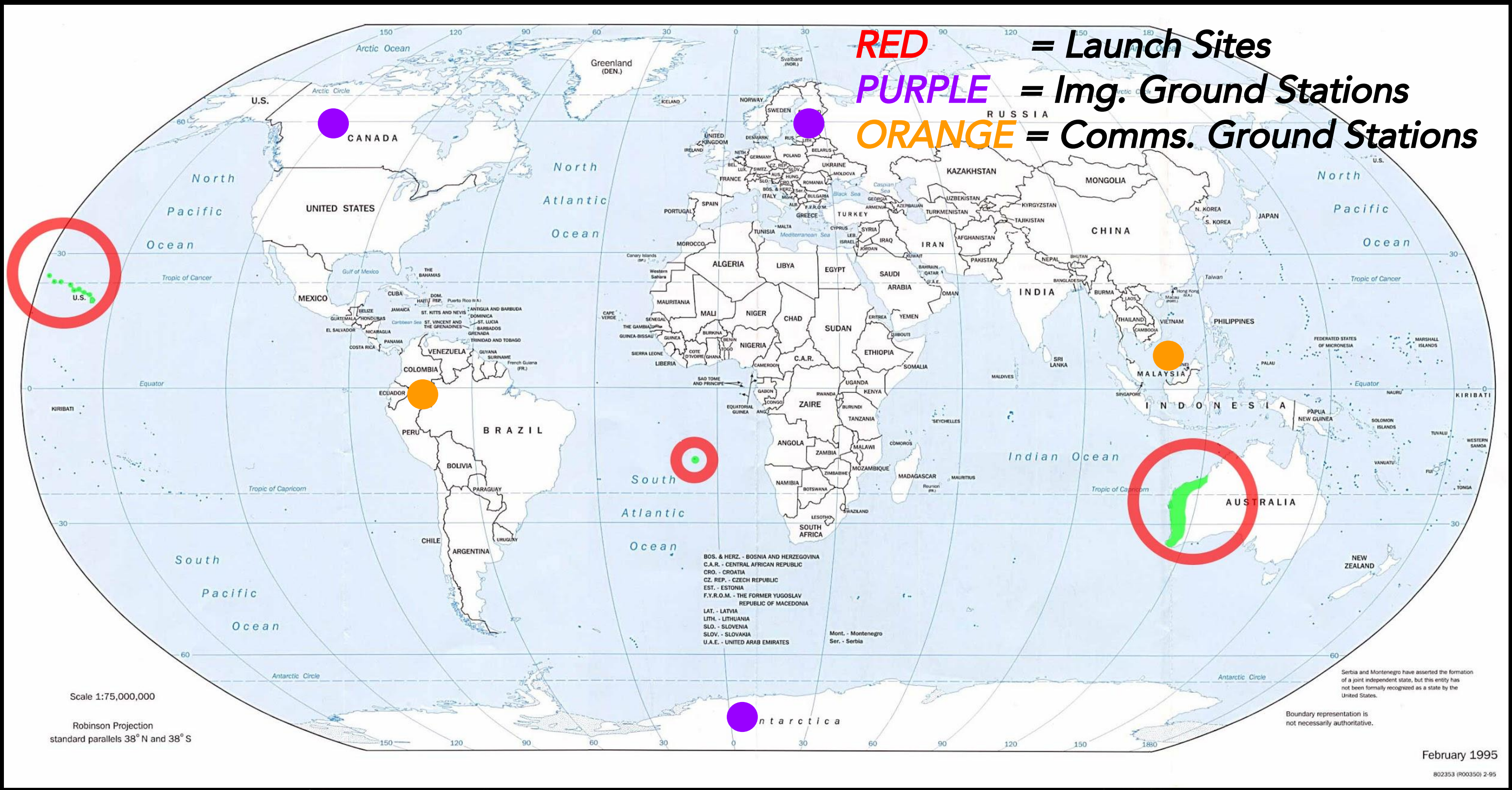
Launch Position

Below vs Above Ground Storage Trade

Horizontal vs Vertical Storage Trade

Ground Stations

Full Ground System



Ground Stations

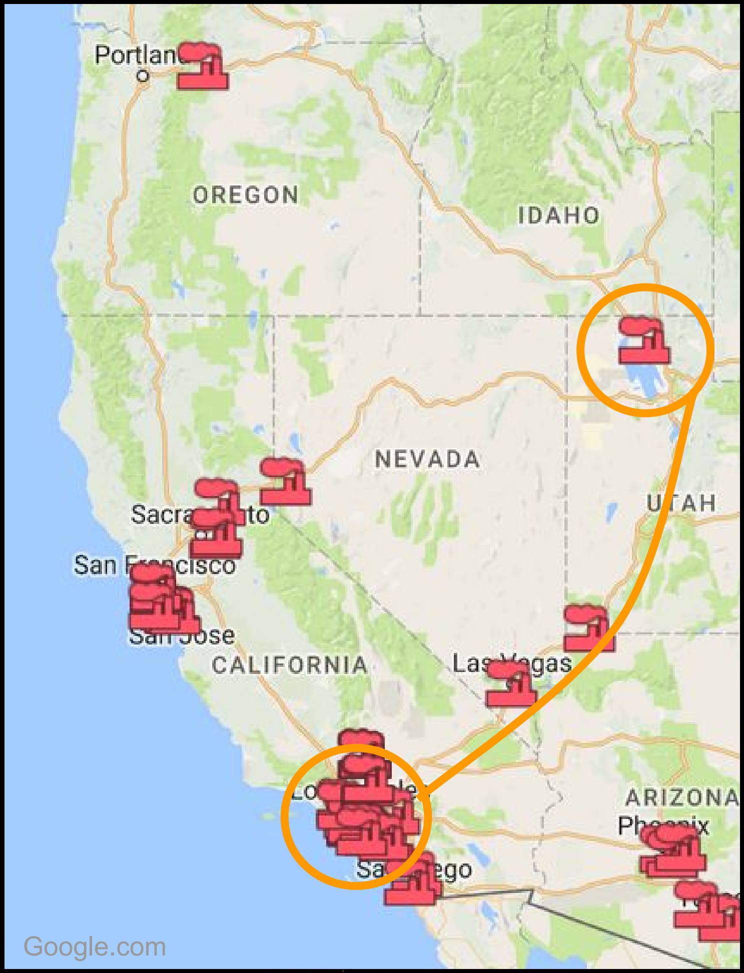
Ground Communications and Downlink Hardware

	Launch Site	Communications	Imaging
Hardware	12dB Yagi w/ Advanced Radio Solutions TAS-50	12dB Yagi	2.3 diameter UHF - KU dual band dishes w/ 48dB peak gain
Elevation Angles	0° - 110°	15° Above horizons	15° Above horizons
Operator/Lender	Minerva System	KSAT/LANSAT	KSAT
Locations	At Launch Sites	Singapore/Ecuador	Sweden/Canada/ Antarctica

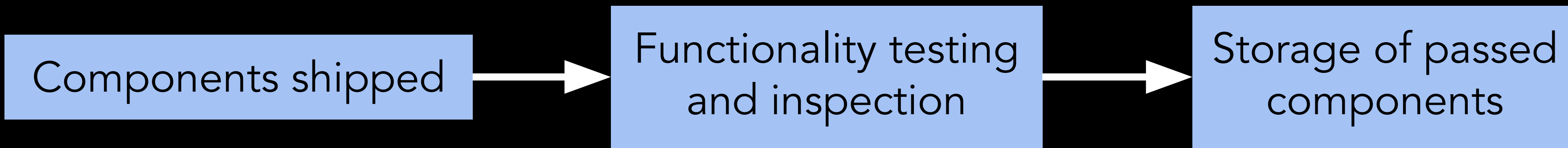
Launch Site Communications Hardware

Manufacturing

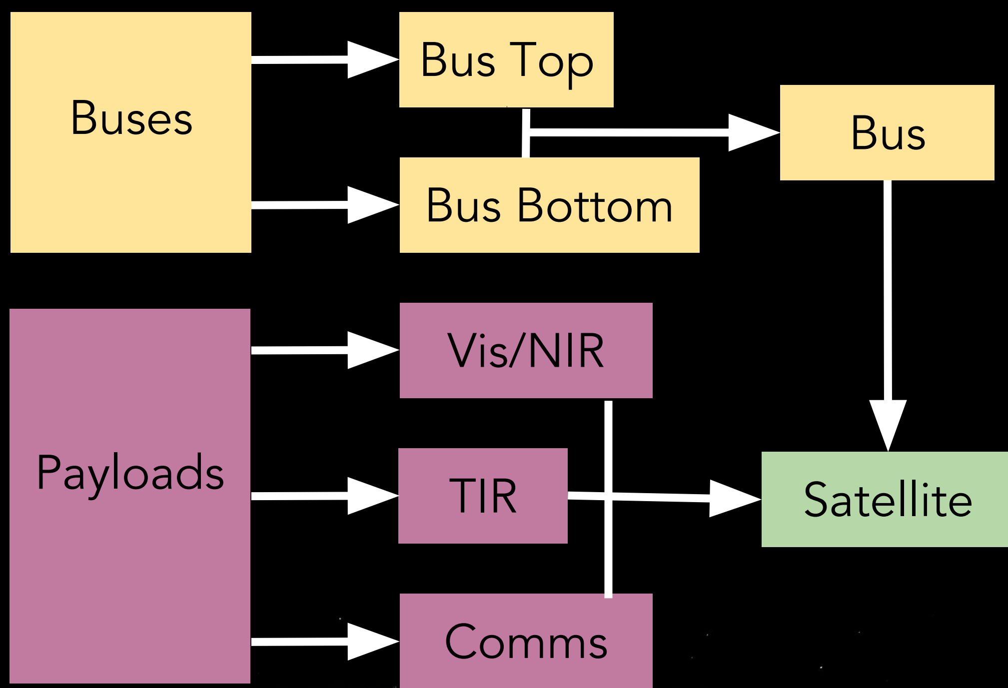
- LA County Manufacturing Facility
  - Launch Vehicles and Satellites in one facility
- Solid Motors from Orbital ATK Utah Facility



Assembly, Integration, and Testing

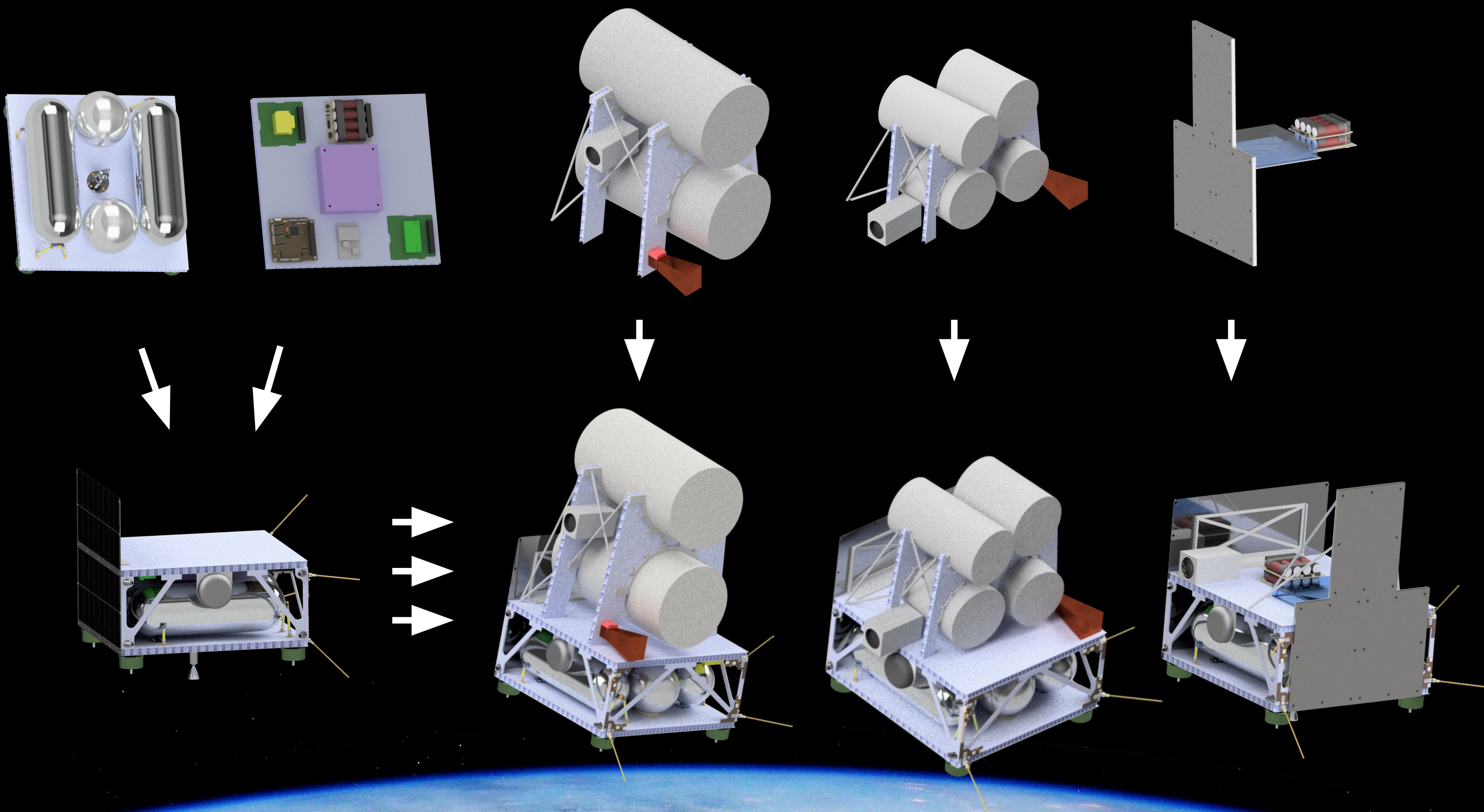


Parallel Integration



Assembly, Integration, and Testing

Parallel lines



Assembly, Integration, and Testing

Qualification Testing

- First Satellite of each type

↓

Acceptance Testing

- Next Satellites of each type
- Used for Flight Testing of launch vehicles

↓

Full-speed Production

- Approximately 2 satellites/week
- Workmanship, functionality testing
- Acceptance tests on every 5th satellite

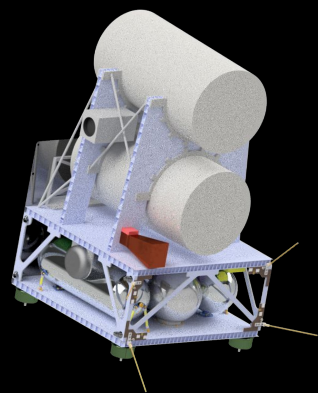
Cost Summary

	LV	Comms	Vis/NIR	TIR
Development & Test	$188 M	$11 M	$16 M	$16 M
Flight System	$65 M	$8 M	$16 M	$4 M
Redundant Units	$25 M	$4 M	$6 M	$3 M
Total	$278 M	$23 M	$38 M	$23 M

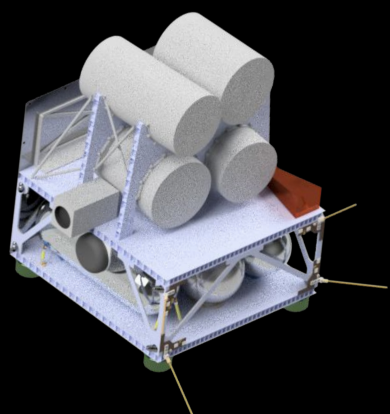
- Aggregate Parametric Cost Model
- Total Program Cost: $362 M
  - Does not include ground systems or launch site

CONCLUSION

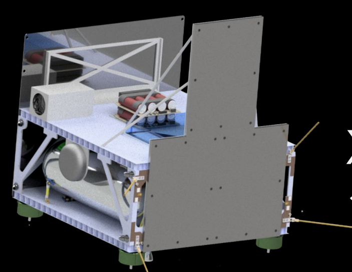
System Summary



x 24
25 kg



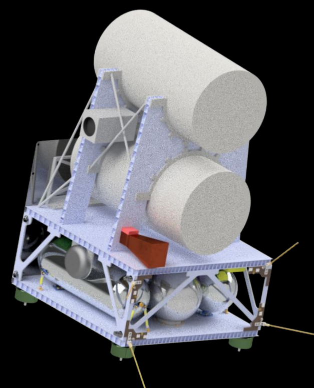
x 4
25 kg



x 16
12 kg

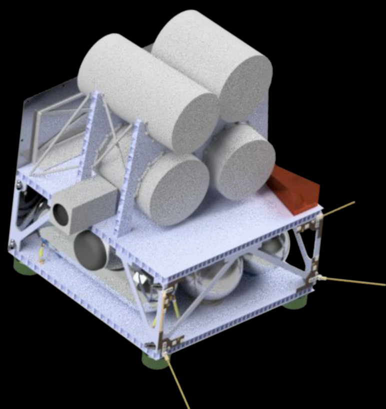
x 11
25 tonnes

System Summary + Redundancy



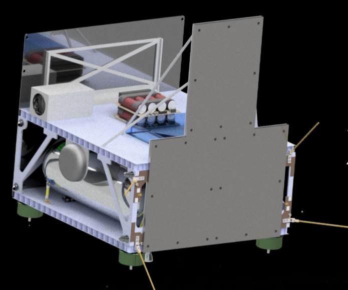
x 24+12

25 kg



x 4+4

25 kg



x 16+12

12 kg

x 11+6

25 tonnes

Moving Forward

- Launch Vehicle
  - Refine structural and thermal analysis
  - Payload environment analysis
  - Further refine trajectories
- Satellites
  - Investigate impact of multiple sets
  - Refine payload designs

Mission Requirements Summary

- 25% capability in 12 hours
- Full capability in 24 hours
- 1 daylight image of full AOI daily
- 3 daylight images of 15% of AOI daily
- Repeater access for 240 minutes daily
- System storable for minimum of 5 years
- 95% reliable after 6 months (at EOL)

SLIDE REPOSITORY

ARCHITECTURE

Mission Trades

Orbital Altitude

Back to presentation

	LEO	MEO	GEO
Time to Orbit			
Radiation Concerns			
Resolution Requirements			
Deorbit in less than 5 years			
Number of Vehicles			

Outcome: **LEO**

Mission Trades

Capability Allocation

Back to presentation

	Same Satellite	Different Satellite
Satellite Complexity		
Optimal Orbit Differences		
Number of Vehicles		

Outcome: **Separate Comms and Imaging Satellites**

Mission Trades

Orbital Variability

Back to presentation

	Variable Orbits	Complete Global Coverage
Number of Satellites		
Number of Orbital Planes		
Launch Site Location		
Excess Coverage		
System Complexity		

Outcome: **Variable Orbits**

Mission Trades

Distribution Scheme

Back to presentation

	LV Burns	Satellite Burns
Time Allocated for Distribution		
ΔV required		
Number of Maneuvers		
Launch Vehicle Complexity		
Satellite Complexity		

Outcome: **Satellites will Distribute Themselves**

Mission Trades

Imaging Spectral Band Allocation Back to presentation

	Separate Satellites	Same Satellite
Thermal Imaging Day of Launch Decision		
Number of Launches		
Coverage Requirements		
Satellite Complexity		

Outcome: **Different satellites for Visible/Near IR and Thermal IR**

Mission Trades

Common Bus

Back to presentation

	Different Bus	Common Bus
Development Cost		
Satellite Operations Differences		
Required Launch Vehicle Capability		

Outcome: **Satellites with a Common Bus**

COMMON BUS

Common Bus - Propulsion

Propulsion: Thruster

- Total Thrust: 5N
  - Minimum Impulse bit: 0.25 N-s
- Mass: 0.38 kg
- Isp: 239-253s
- Power: 8 Watts
- LMP-103s Green Propellant
  - Ammonium dinitramide, Methanol, Ammonia, and Water
  - Density: 1.24 g/cm^3
  - Temperature Range: -5 to 50 C
  - Condensation of ADN: ~ -7 C
  - Freezing: ~ -90 C

Back to prop

Common Bus - Power

Baseline Assumptions for battery/solar panel sizing

	Assumption	Rationality
Solar Cell BOL Absorptivity	0.25	Reasonable (eg. GaAr TJ)
Solar Cell Degradation	2.75 %/yr	Reasonable (eg. GaAr in LEO)
Packing Density	0.78	Conservative
Battery Charge/Discharge & PDU Efficiencies	90%/80%	Reasonable
Battery Energy Density	100 Whr/Kg	Reasonable (eg. Li-Ion)
Battery Max. Depth of Discharge	100%	Reasonable (~180 cycles)

Common Bus - Structure

Satellite Structure: Honeycomb

Core:

- Material: Al 5056
- Density: 0.064 g/cc (4.2 pcf)
- Height: 9.5 mm
- Max Stress: 747.4 kPa
- F.O.S: 1.74

Face-sheets:

- Material: Al 2024
- Thickness: 0.254 mm
- Max Stress: 186.6 MPa
- F.O.S: 1.74

Loading:

- Axial Load: 1216.2 N
- Lateral Load: 810.8 N

Return to Common Bus Structure

Return to Common Internal Components

Common Bus - Structure

Structure: Corner Support Posts

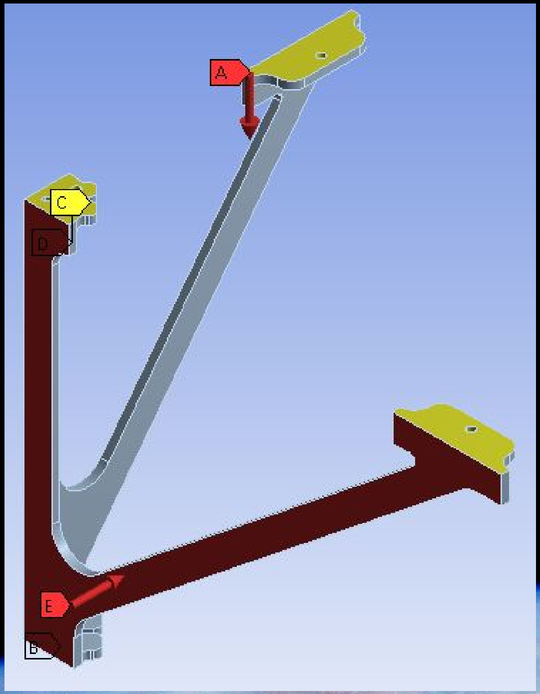
- Material: Al 6061
- Thickness: 3 mm
- F.O.S: 2.5

- Axial Load: 300 N
- Lateral Load: 125 N
- Max Stress: 112.6 MPa
- Max Disp: 0.6 mm

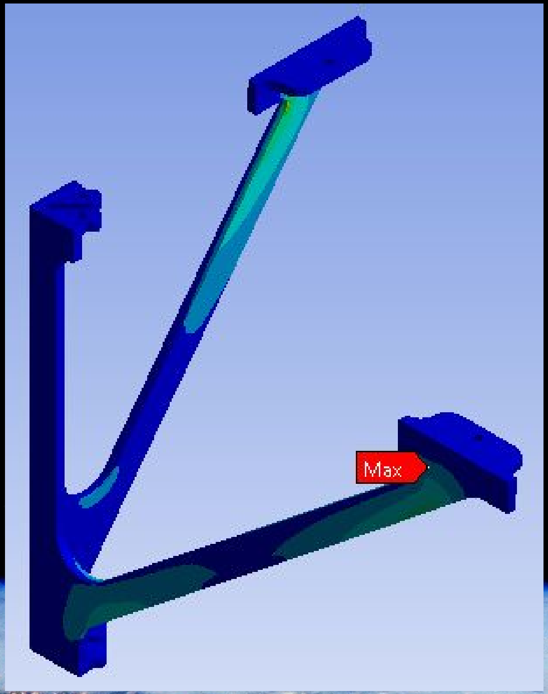
Return to Common Bus Structure

Return to Common Internal Components

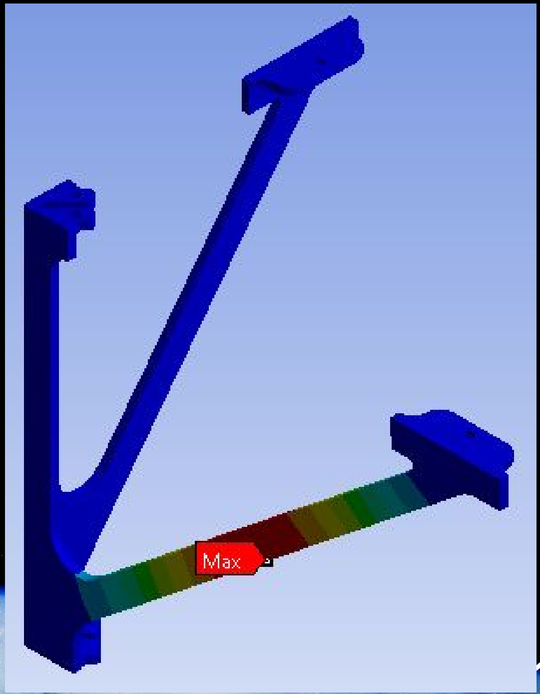
Boundary Conditions



Axial Stress



Lateral Displacement



IMAGING

Imaging Sensor Type Trade

[Link Back to: Imaging Trades Slide]

	VISNIR				TIR			
Metrics	Weight	Pushbroom	Pushwhisk	Matrix Starer	Weight	Pushbroom	Pushwhisk	Matrix Starer
Dwell Time	0.4	7	6	8	0.5	7	6	10
Mechanical Complexity	0.6	7	5	4	0.7	6	4	3
Pointing Requirements	0.3	7	8	5	0.5	6	9	8
Optical Complexity	0.5	5	6	5	0.4	4	6	4
Cost	0.4	3	4	3	0.4	4	5	3
Smear	0.3	5	4	3	0.6	4	3	5
Reliability	0.7	8	6	6	0.5	8	6	5
Power	0.3	9	8	7	0.3	8	7	6
Useful Data (%)	0.7	7	7	9	0.4	8	8	10
Operational Delay	0.4	8	6	8	0.4	5	4	6
Total		30.7	27.5	27.5		27.9	26.4	27.6

Imaging Sat Capability Trade

Metrics Considered:

- Data Generation
- Sensor Size
- Payload Size
- No. of Satellites
- Complexity
- Data Downlink
- Power Cost
- Pass Utilization
- Mass
- Size
- Power Requirement
- Control Capacity
- Phasing Time
- Phasing DeltaV

Link Back to:
Imaging Trades Slide

Imaging - ADCS

ADCS: Pointing Budget (While Imaging)

	Source	X-Axis [deg]	Y-Axis [deg]	Z-Axis [deg] Through Optics
Thermal	Thermal Deformation	0.0067	0.0067	0.0054
AD Sensors	Star Tracker Accuracy	0.0019	0.0019	0.011
	Star Tracker Misalignment	0.059	0.065	0.001
	Gyroscope Misalignment	0.036	0.036	0.036
	Gyroscope Angular Random Walk	1.1e-3	1.1e-3	1.1e-3
	Gyroscope Bias Instability	1.4e-04	1.4e-04	1.4e-04
	Gyroscope Scale Factor Error	4.1e-06	7.3e-06	4.2e-06
Actuator	RCS Thruster Misalignment	0.003	0.005	0.008
Totals	Requirement	0.3	0.3	0.3
	Contingency	0.2	0.2	0.2
	Total (RSS) 1-Sigma	0.0831	0.0893	0.0465

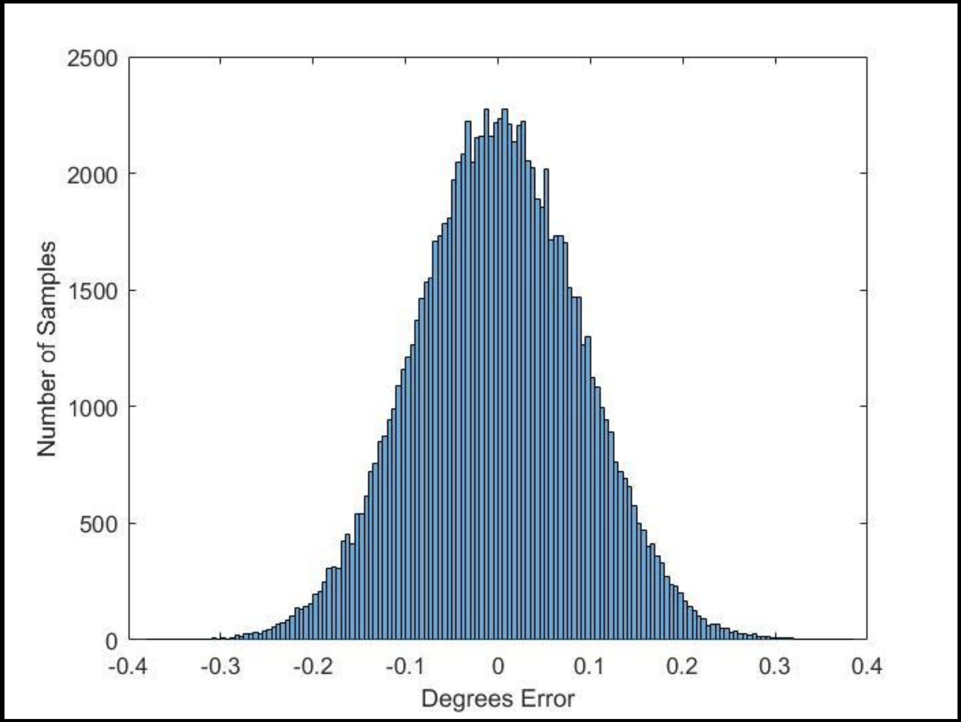
Monte carlo pointing analysis

Back to Imaging - ADCS
Attitude Determination

Monte Carlo Pointing Simulation

Simulation Parameters:

- 100,000 random samples in normal distribution
- Worst case pointing error of 0.08926 degrees
- 1-σ standard deviation equal to nominal pointing error
  - Error: 0.089 1-σ



Imaging Comms Downlink

Link Budget Downlink of Images	
Frequency	13.75 GHz (Ku)
Noise Temp	285 K
Space Loss	180 dB
Signal to Noise Ratio	9 dB
Data Rate	200 Mbps
Transmitter Gain	14 dB
Receiver Gain	48 dB
Power (RF)	10 W
Margin	4.3 dB

Common Bus - Power

Baseline Assumptions for battery/solar panel sizing

	Assumption	Rationality
Solar Cell BOL Absorptivity	0.25	Reasonable (eg. GaAr TJ)
Solar Cell Degradation	2.75 %/yr	Reasonable (eg. GaAr in LEO)
Packing Density	0.78	Conservative
Battery Charge/Discharge & PDU Efficiencies	90%/80%	Reasonable
Battery Energy Density	100 Whr/Kg	Reasonable (eg. Li-Ion)
Battery Max. Depth of Discharge	100%	Reasonable (~180 cycles)

Return

Imaging - Thermal

Thermal: Polar Orbit - Transient (Hot Case)

Back to presentation

Component	Min Temp (°C)	Max Temp (°C)
Propellant	2.8	9
Ku Horn Amplifier	22	44
Optical Payload	16	39
Batteries	30	43
Gyro	44	54
GPS Receiver	42	50
TTC Radio	30	48
Onboard Processor	38	44
Star Tracker	36	50

Imaging - Thermal

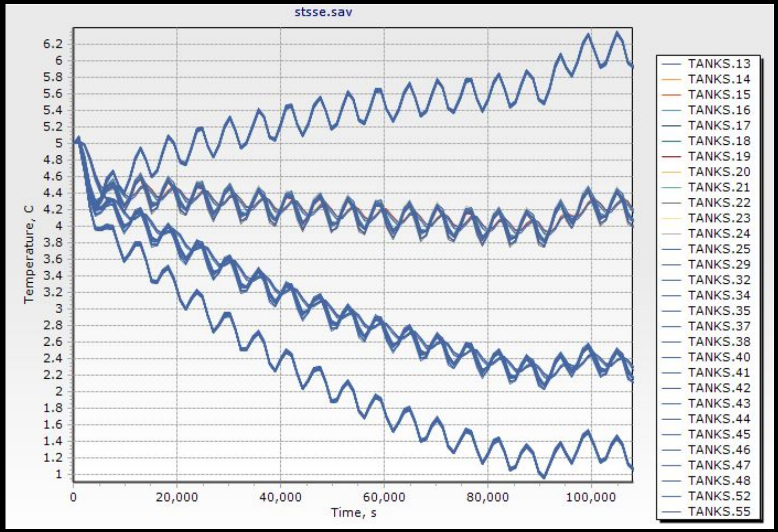
Back to presentation

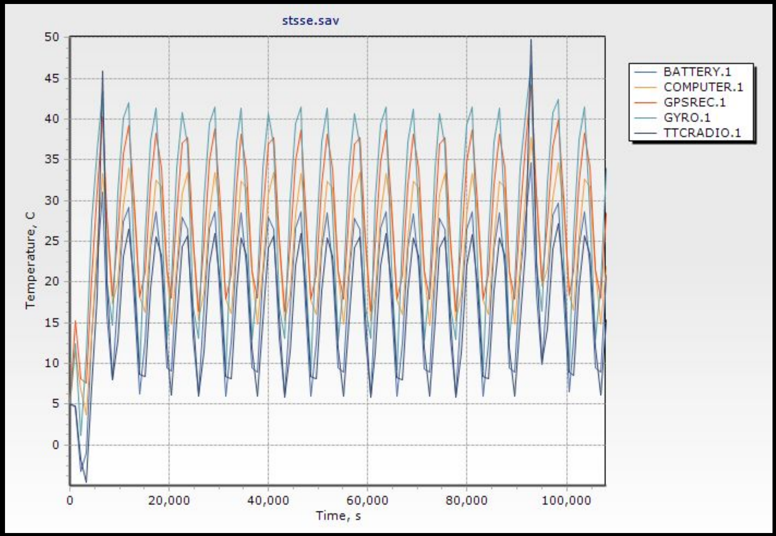
Thermal: Sun Synch Orbit - Transient (Cold Case)

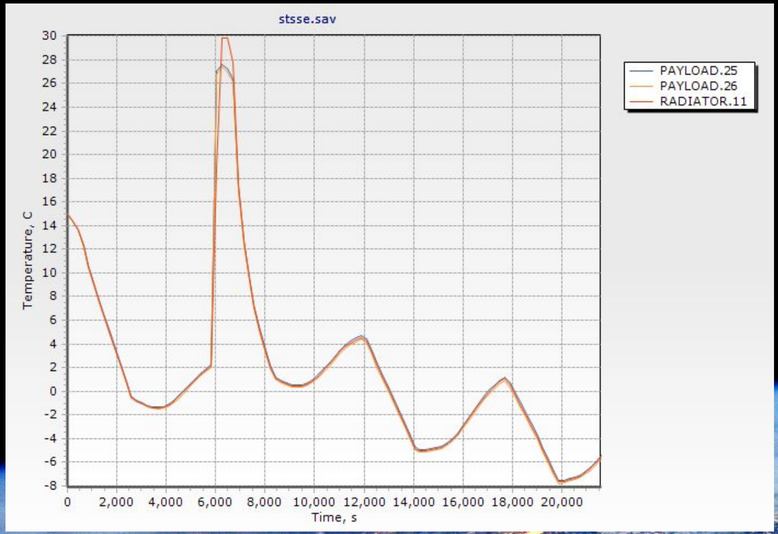
Component	Min Temp (°C)	Max Temp (°C)
Propellant	0	6
Ku Horn Amplifier	-7	25
Optical Payload	-5	30
Batteries	8	26
Gyro	10	43
GPS Receiver	17	38
TTC Radio	6	48
Onboard Processor	15	37
Star Tracker	10	43

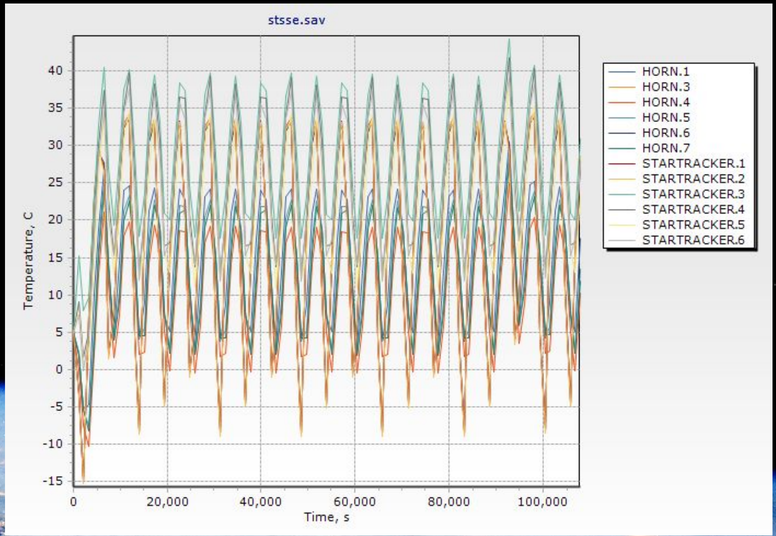
Imaging - Thermal

Sun Synch Orbit - Transient (Cold Case)



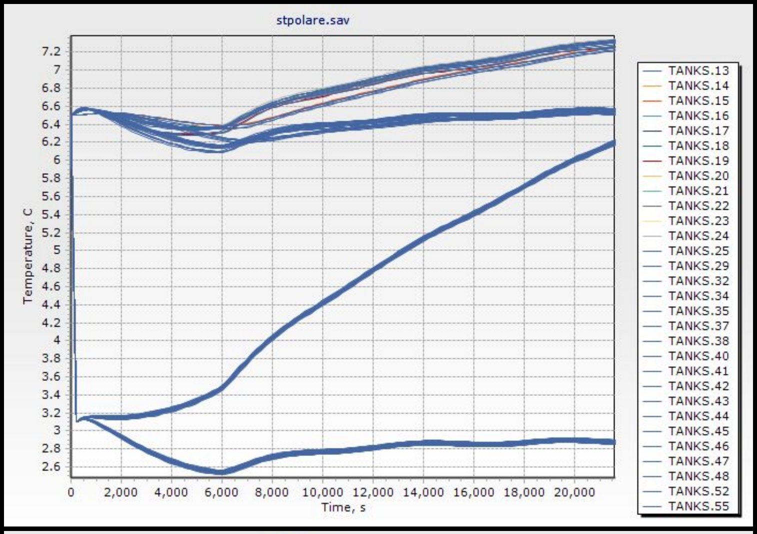


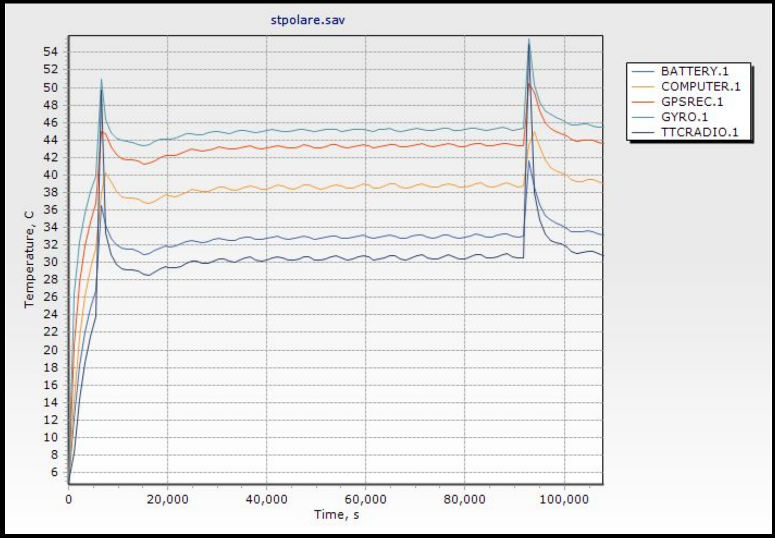


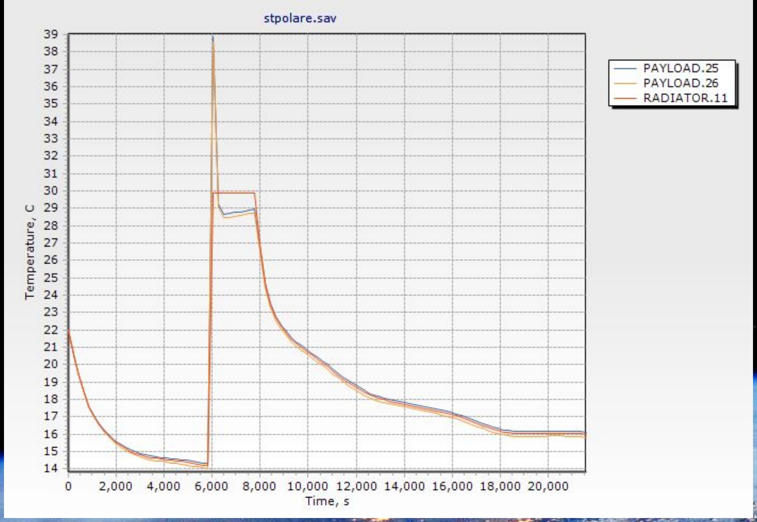


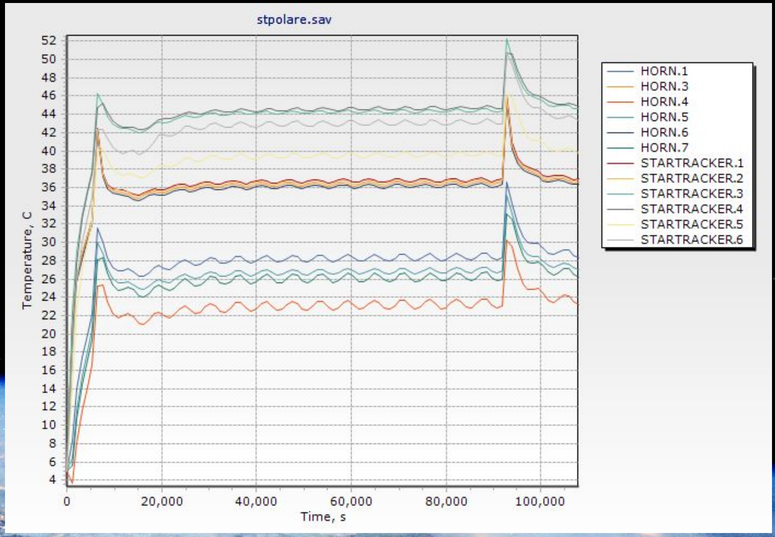
Imaging - Thermal

Polar Orbit - Transient









Imaging - Thermal

Imaging Sat Operating Temps

Satellites	0 value if unknown	
	Component (Link)	Thermal Op. Range
Common		Kelvin (K)
ADCS	Star Tracker	233-353
	Rate Gyro/Accelerometer	233 to 358
	Position Sensor	233 to 358
	Position Sensor Antenna	233 to 358
	RCS Thruster	283 to 368
Propulsion	Engine	
	Piping/Valves	
Structure	Frame/Harnessing	78 to 336
Power	Batteries	233 to 358
	Solar Cells	173 to 398
	Wiring	
	PDU	253 to 333
C&DH	Satellite Processor	248 to 333
TT&C Comms	Antenna	233 to 353
Unique		
Propellant	Phasing Propellant	268 to 323
	Deorbiting Propellant	268 to 323
	Orbital Maintenance Propellant	268 to 323
	Pressurant/ RCS Prop	
	LMP Fuel Tanks	
	Pressurant Tank	244 to 344
Thermal	Heater	
	Cooling	
	MLI	133 to 473
Payload	Focal Plane Array	263 to 323
	Focal Plane Electronics	
	Optics + housing	263 to 323
Downlink Comms	Antenna	233 to 353
	Amplifier	233 to 358
TT&C Comms	Radio	238 to 358
C&DH	Imaging Processor	253 to 333

COMMUNICATIONS

Orbits

Constellation Parameters

Altitude	Inclination	RAAN Spacing (Planes)	True Anomaly Spacing (Satellites)	Eccentricity
625 ± 7 km	Latitude ± 0.1°	Equal ± 6°	40 ± 6°	0 + 1e-3

Constellation Scheme vs Coverage Latitude

Latitude Bin	0°-10°	10°-25°, 65°-90°	25°-65°
No. of Satellites	16	12	16
No. of Planes	4	3	4

*0-16° covered by 16° inclination from St. Helena launch site

Comms - ADCS

ADCS: Pointing Budget (TT&C)

	Source	**X-Axis [deg]**	**Y-Axis [deg]**	**Z-Axis [deg] Through Omni Antenna**
Environment	Thermal Deformation	0.0067	0.0067	0.0054
AD Sensors	Star Tracker Accuracy	0.002	0.002	0.01
	Star Tracker Misalignment	0.0588	0.064681	0.001
	Gyroscope Misalignment	0.036	0.036	0.036
	Gyroscope Angular Random Walk	0.00125	0.00125	0.00125
	Gyroscope Bias Instability	1.39E-04	1.39E-04	1.39E-04
	Gyroscope Scale Factor Error	3.00E-05	9.50E-06	2.75E-05
Actuator	RCS Thruster Misalignment	0.003	0.0051	0.0083
Totals	**Requirement**	**-**	**10**	**10**
	Contingency	**0.2**	**0.2**	**0.2**
	Total (RSS) 1-Sigma	**0.0692**	**0.0892**	**0.0446**

Comms - Thermal

Thermal: 90º Beta Angle - Transient

Back to presentation

Component	Min Temp (ºC)	Max Temp (ºC)
Propellant	7	32
Batteries	-6	48
Gyro	8	60
GPS Receiver	0	52
TTC Radio	-7	45
Onboard Processor	-5	51
Star Tracker	-3	50
UHF Payload	13	77

Comms - Thermal

Thermal: 0º Beta Angle - Transient

Back to presentation

Component	Min Temp (ºC)	Max Temp (ºC)
Propellant	10	21
Batteries	14	38
Gyro	29	50
GPS Receiver	20	42
TTC Radio	14	33
Onboard Processor	17	40
Star Tracker	0	40
UHF Payload	-3	85

Comms - Thermal

Communications Sat Operating Temps

Satellites	0 value if unknown	
Subsystems	Component (Link)	Thermal Op. Range
Common		Kelvin (K)
ADCS	Star Tracker	233-353
	Rate Gyro/Accelerometer	233-353
	Position Sensor	233-358
	Position Sensor Antenna	
	RCS Thruster	283-368
Propulsion	Engine	
	Piping/Valves	223 to 323
Structure	Frame/Harnessing	78 to 336
Power	Batteries	233 to 358
	Solar Cells	173 to 398
	Wiring	
	PDU	253 to 333
C&DH	Satellite Processor	248 to 333
TT&C Comms	Antenna	253 to 333
Unique		
Propulsion	Phasing Propellant	268 to 323
	Deorbiting Propellant	268 to 323
	Pressurant/ RCS Prop	268 to 323
	LMP Tanks	244 to 344
	Pressurant Tank	244 to 344
Thermal	Heater	
	Cooling	
	MLI	133 to 473
Payload	Custom Radio	218 to 398
	Patch	
TT&C Comms	Radio	238 to 358

Repeater Payload

Other Considerations

- Doppler Shift
  - UHF max doppler shift seen by S/C and AOI: 10.17 kHz
  - Channel Bandwidth: 12.5 KHz
  - Software Defined Radio: Helps counteract shift
- Encryption
  - Only want people in the AOI to receive our communication
  - AES/DES encryption available on our baseline radio

Repeater Operations

Minerva Channel Scheme			
Channel Number	Channel Description	Uplink frequency (MHz)	Downlink Frequency (MHz)
1	Schedule/General Broadcast	410.6625	420.6625
2	Food/Water	411.0875	421.0875
3	Medical Aid (non-life threatening)	411.5125	421.5125
4	Evacuation	411.9375	421.9375
5	Life/death/SOS (1)	412.3625	422.3625
6	Life/death/SOS (2)	412.7875	422.7875

UHF Federal Incident Response Interoperability			
Channel Number	Channel Description	Uplink frequency (MHz)	Downlink Frequency (MHz)
1	Calling	410.2375	410.2375
2	Ad hoc assignment	410.4375	410.4375
3	Ad hoc assignment	410.6375	410.6375
4	SAR incident Command	410.8375	410.8375
5	Ad hoc assignment	413.1875	413.1875
6	Interagency Convoy	413.2125	413.2125

LAUNCH

Launch - Trades

Air vs. Land vs. Sea

Return

Metric	Air	Land	Sea	Weight
Development Cost	5	8	4	0.6
Maintenance Cost	6	8	3	0.6
Launch Timeliness	5	7	3	1
Regulations	4	6	8	0.4
Complexity	4	9	5	0.8
# launches from each site	3	8	7	0.4
Payload Size	5	9	8	0.7
People Risk	6	8	9	0.3
Launch Location	8	5	8	0.5
Total	26.9	40.6	29.5	

Launch - Structures

- Expected maximum loading during flight:

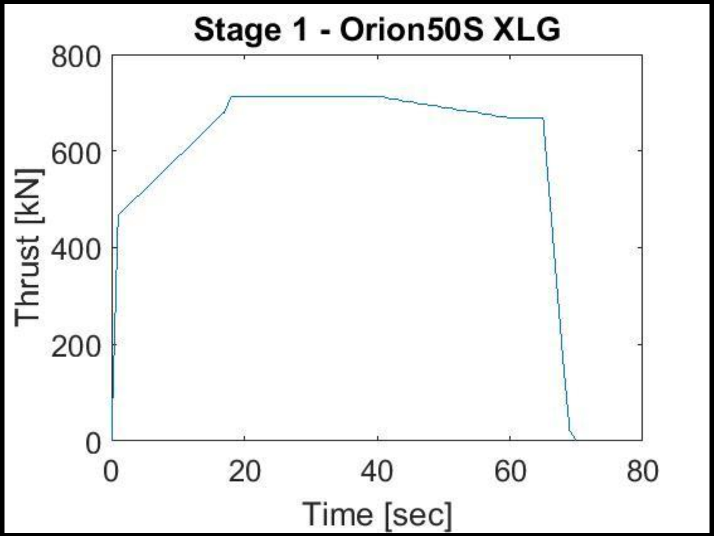
Event	Altitude (km)	Gravity (g's)	Thrust (kN)	Drag (kN)	Dynamic Pressure (kPa)
Liftoff & Atmospheric Flight	0	10.7	667	84.6	80.4
Stage 1 Engine Cutoff	47.5	9.7	N/A	3.5	5.5
Coast #1	47.5 to 53.7	N/A	N/A	2.55	4.03
Stage 1 Jettison & Stage 2 Ignition	53.7	3.7	154	174	8.02
Stage 2 Flight	53.7 to 160	1	154	174	8.02

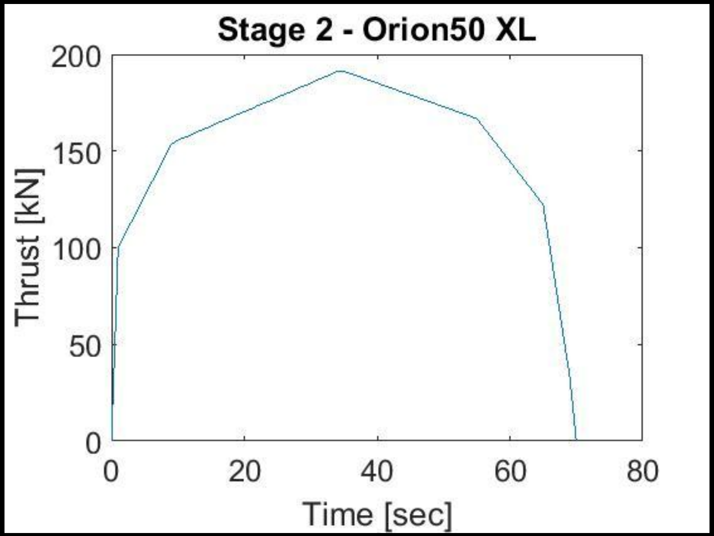
Launch - Structures

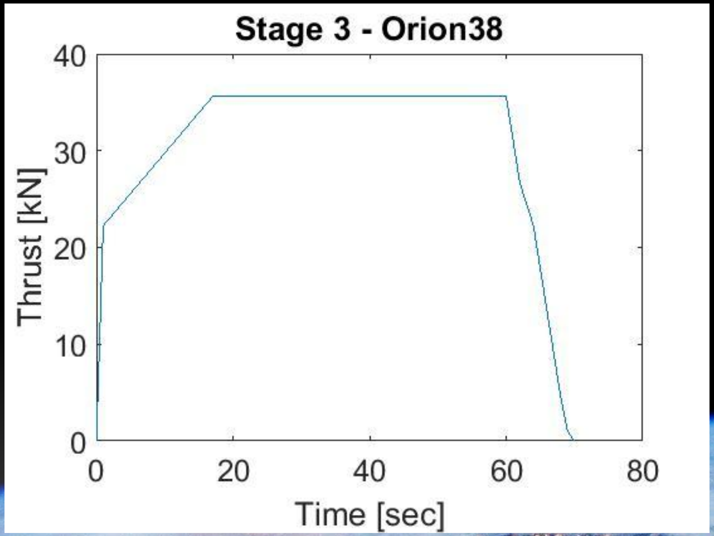
- Expected loading during stages of flight cont...

Event	Altitude (km)	Gravity (g's)	Thrust (kN)	Drag (N)	Dynamic Pressure (Pa)
Stage 2 Engine Cutoff	160.1	N/A	N/A	N/A	N/A
Stage 3 Ignition	560	3.8	32	N/A	N/A
Stage 3 Flight	568	9.7	32	N/A	N/A

Orbit Injection Accuracy







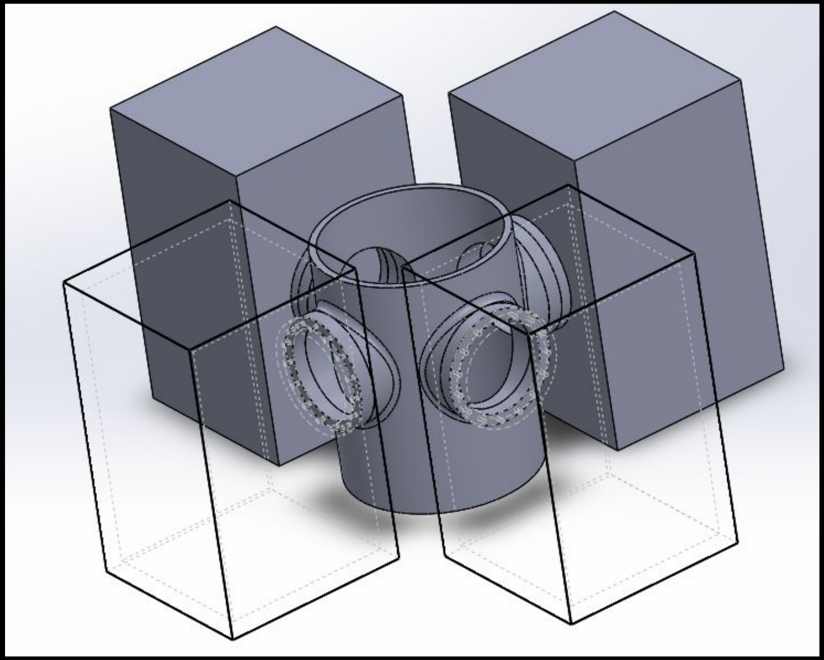
What we do:

-Carmelle's results

Launch - Payload Integration

Radial Mounting

- Ability to deploy (2) sats quickly
- High stress areas near rings
- Additional structural mass added for cylindrical mounting component



Return

Launch - Payload Integration

Ejection Spring

- Spring Constant = 300 N/m
- Mass = 29g each (x16 per launch vehicle)
- Wire Diameter (mm): 1.72
- Outer Diameter (mm): 25.4
- Free Length(mm): 70.00
- # of Active Coils: 19
- Spring Constant (N/m): 300
- Material: Stainless 316 ASTM A316
- Min Safe Travel Height (mm): 36.12
- Required Loaded Height (mm): 40

Return

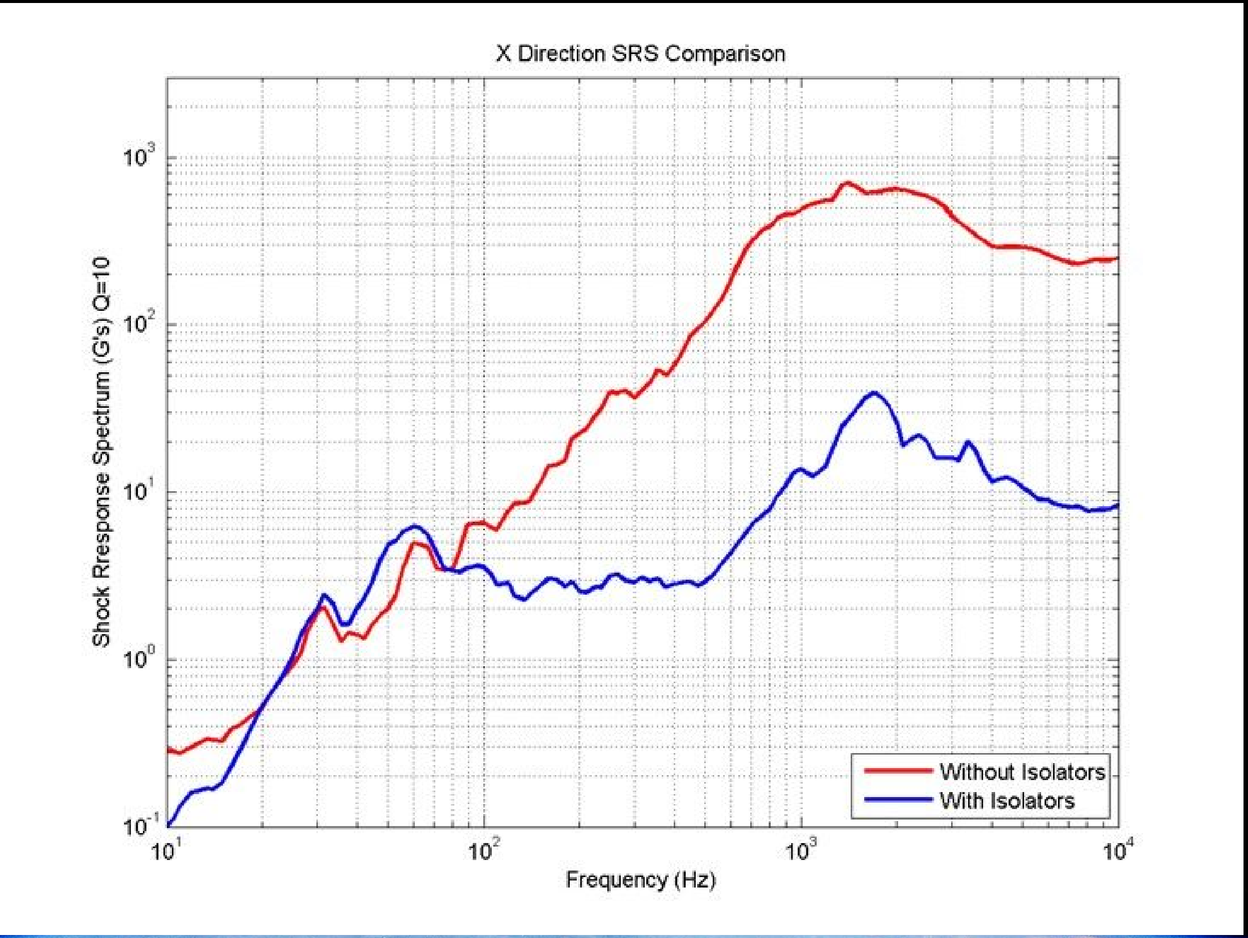
Launch - Payload Integration

Payload Injection

- Satellites want to minimize ejection velocities
  - Rotational, positional, tumbling
- Direction of deployment consideration
  - Affects sat configuration on LV
  - Small ejection velocities make direction negligible
  - All satellites should deploy in same direction
- Pyros vs actuators for release mechanism
  - Actuators produce no shock but require more power
  - Pyros allow for a simpler separation system
- Spring system vs thrusters for ejection
  - Propellant plume can damage other satellites
  - Springs can be designed and sized to eject satellites at specific velocities

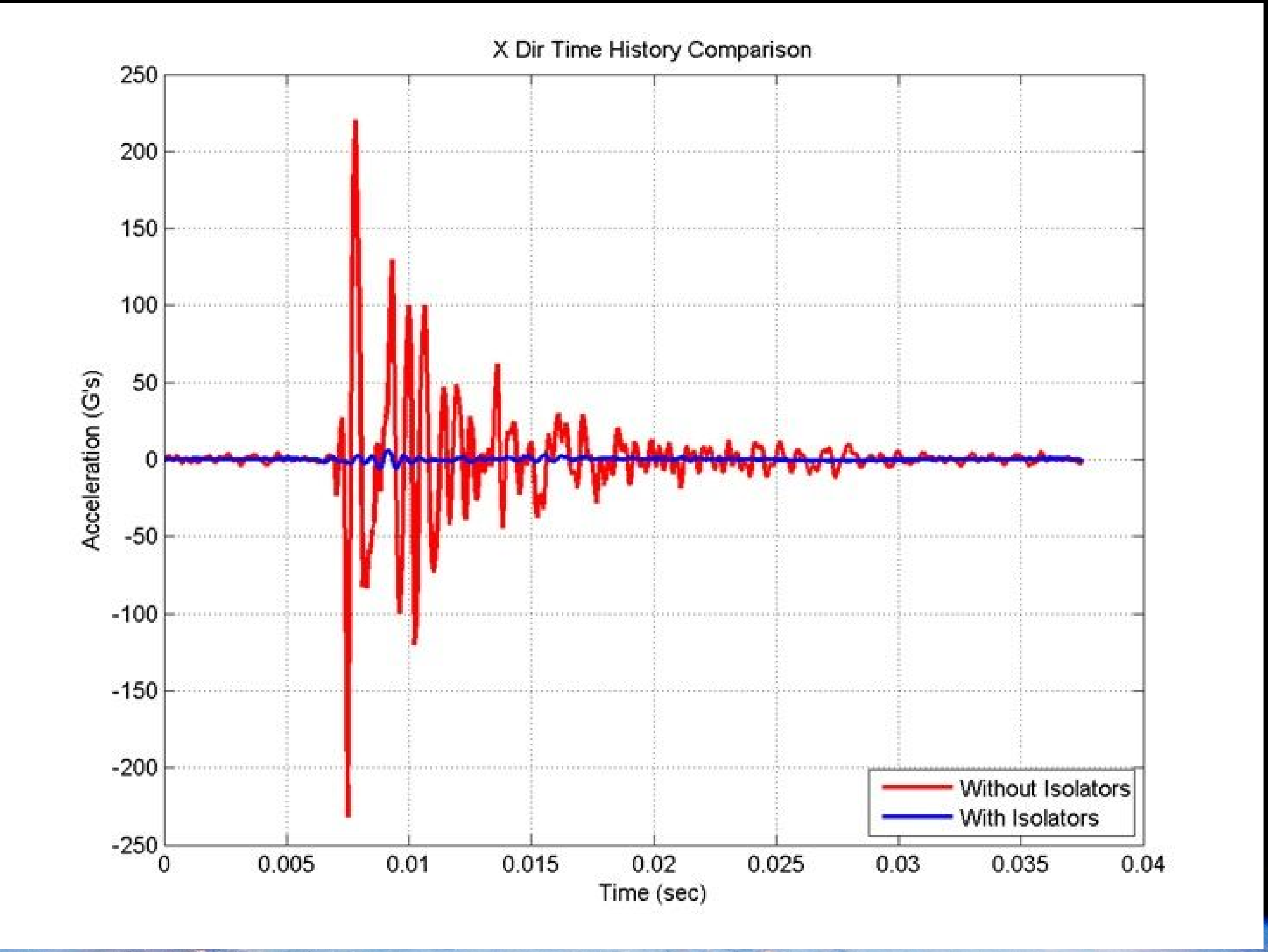
Launch - Payload Integration

Shockwave Isolator Data



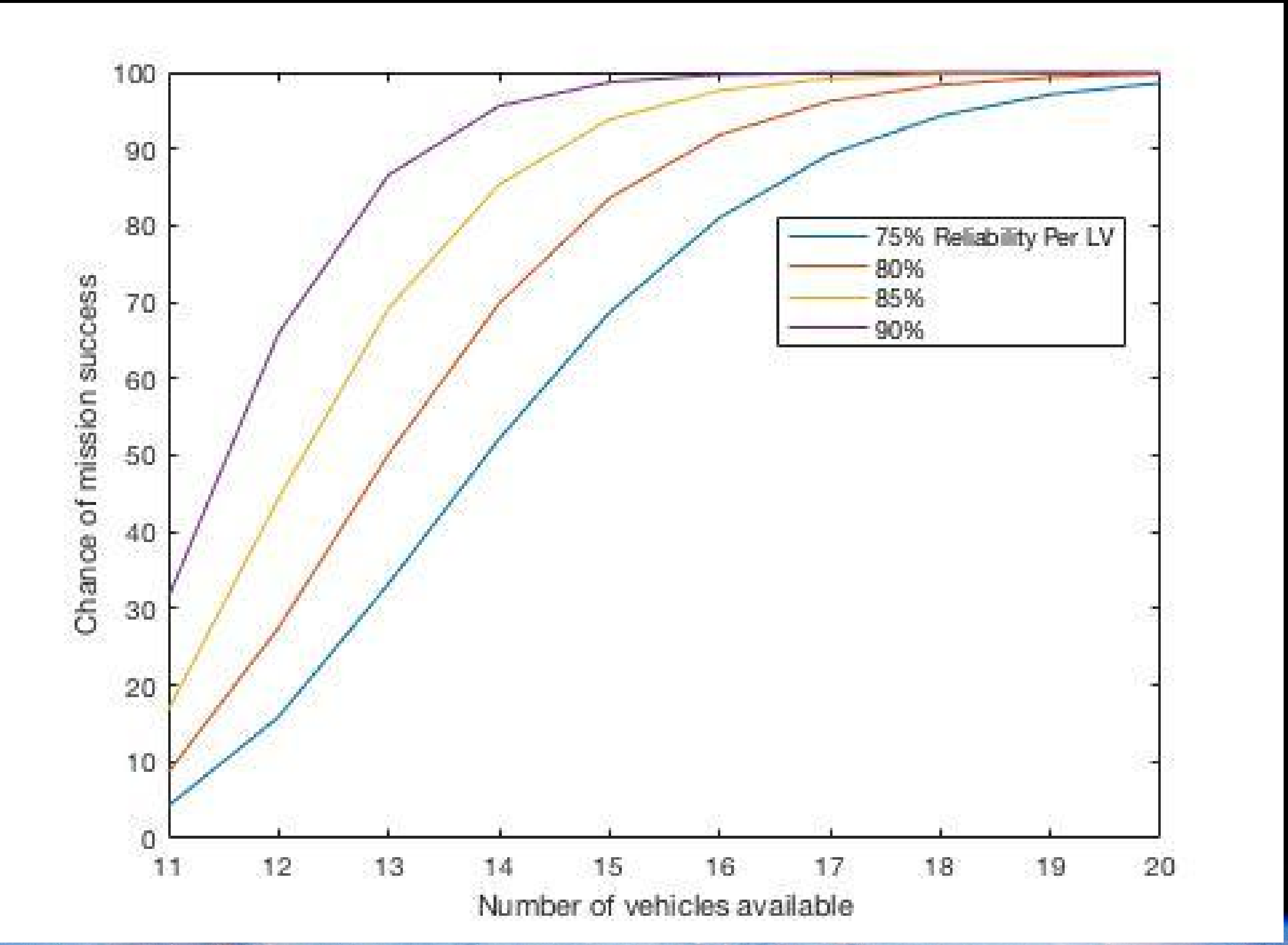
Launch - Payload Integration

Shockwave Isolator Data



Launch - Redundancy

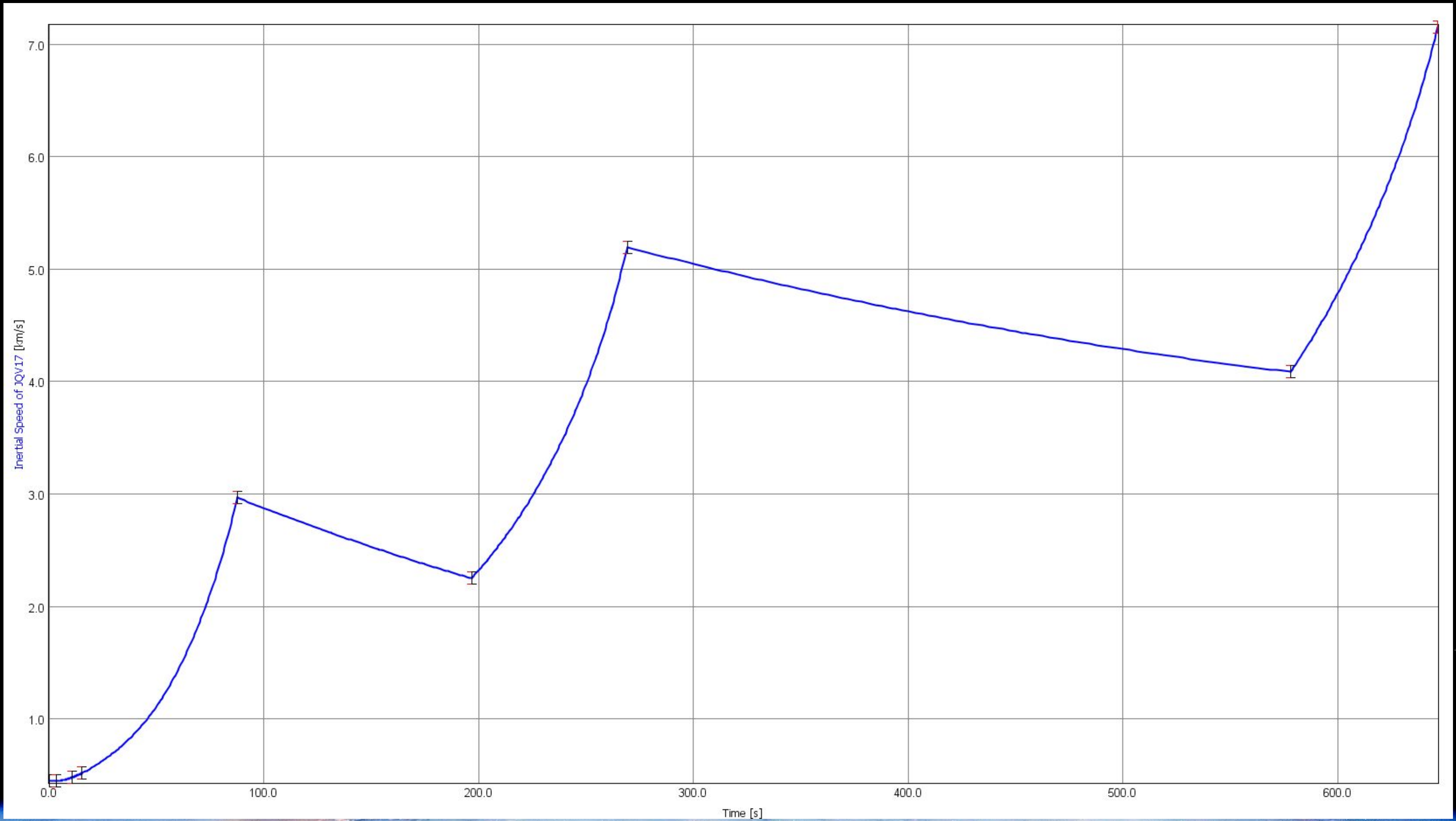
Number of Vehicles Required for Mission Success



Return to Launch Slide Distribution

Launch - Trajectory Velocity Bleed

- 43.6 kg Comms Package, 625 x 1139 km, 15.95 degree inclination



Launch - Stage Separation

Hot Separation

Launch - Build vs. Buy

Decision: Build

Return

- LV purchase is unprecedented
- Buying ICBMs is difficult
- Will need a large number and most LV manufacturers don't have the capability to build that many
- Difficult to buy a launch vehicle and use your own operations system
  - Almost all companies that manufacture LVs require you to use their operating systems
- Building our own LV allows for customization

Launch - Solid vs Liquid

Return

Type of Fuel:	Performance	Complexity of Flight	Assembly	Cost	De-Orbit	Complexity of Design	Storage	Value:
Weight:	0.2	0.3	0	0.05	0.2	0.2	0.05	---------------------
Solid (HTPB)	Higher Isp/thrust	maneuvers to spend fuel	Simple design	Much cheaper	retro solids added on	Simple design	Good storage	4.2
-------------------------	6	3	6	5	2	6	5	---------------------
Liquid (LMP-103S)	Monoprop	Standard flight trajectory	more complex	More expensive	Restart capabilities	More complex	Slightly more restricted	4.55
-------------------------	3	6	3	2	6	3	5	---------------------

- Solid propellant has better performance by thrust and Isp metrics
- Liquid propellant has benefit of easier variability of orbits for launch
- Decided to baseline HTPB solid monopropellant due to storability capabilities, acceptable performance metrics, and simplicity of design integration

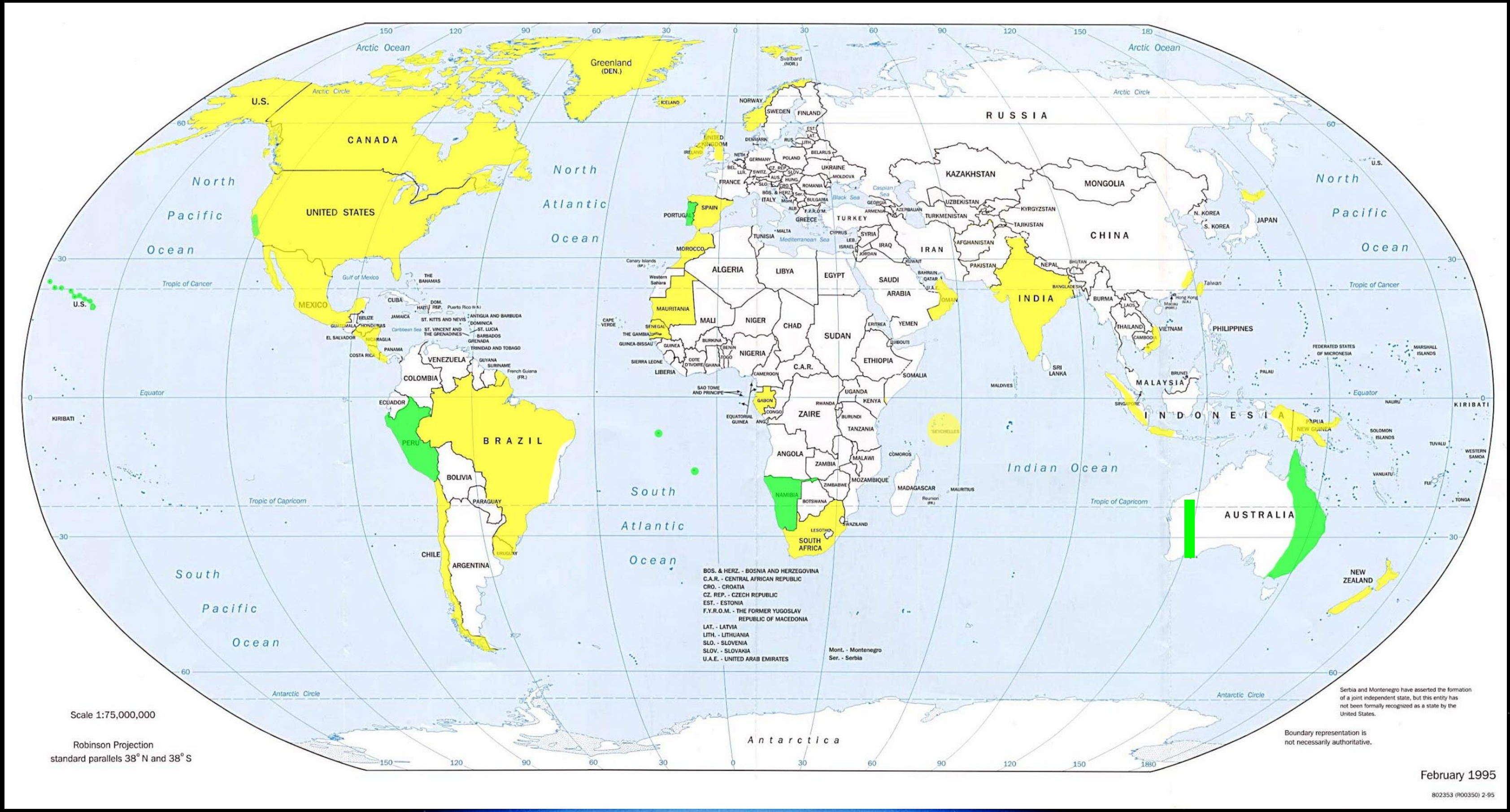
Launch - Power Breakdown

Launch Vehicle Power Budget					
	Component	**Quantity**	**Watt-Hour**	**Time (sec)**	**Watt**
Stage 1,2,3	Igniter	3	0.0007	0.006	420
Interstage 1,2	Separation Bolts	12	0.00090405	0.0021525	1512
Forward Equipment Bay	Computer	3	2.520166667	1512.1	6
	IMU	2	5.250347222	1512.1	12.5
	Radio	1	3.362847222	968.5	12.5
	Autonomous Flight Termination System	1	11.76077778	1512.1	28
	Cold Gas Thrusters	16	116.7222	1050.5	400
	GPS	1	0.5380555556	968.5	2
Payload Area	Payload Separation System	16	0.001777777778	0.01	640
		Total Watt-Hours	141.5049		

GROUND

Ground - Launch Sites

Acceptable possible launch locations



Return to Ground Slides

Ground - Build vs. Use Pre-existing Launch Site

Return

Decision: Build

- Can't use any government or military infrastructure
    - Eliminates a good number of pre-existing launch sites
- 24 hour requirement means optimal launch locations are limited
    - Only 9 areas that meet our criteria

Ground - Air vs. Land vs. Sea Trade

Metric	*Air**	*Land*	*Sea*	*Weight*
Development Cost	5	8	4	0.6
Maintenance Cost	6	8	3	0.6
Launch Timeliness	5	7	3	1
Regulations	4	6	8	0.4
Complexity	4	9	5	0.8
# launches from each site	3	8	7	0.4
Payload Size	5	9	8	0.7
People Risk	6	8	9	0.3
Launch Location	8	5	8	0.5
Total	26.9	40.6	29.5	

Ground

Launch Ground System Trade

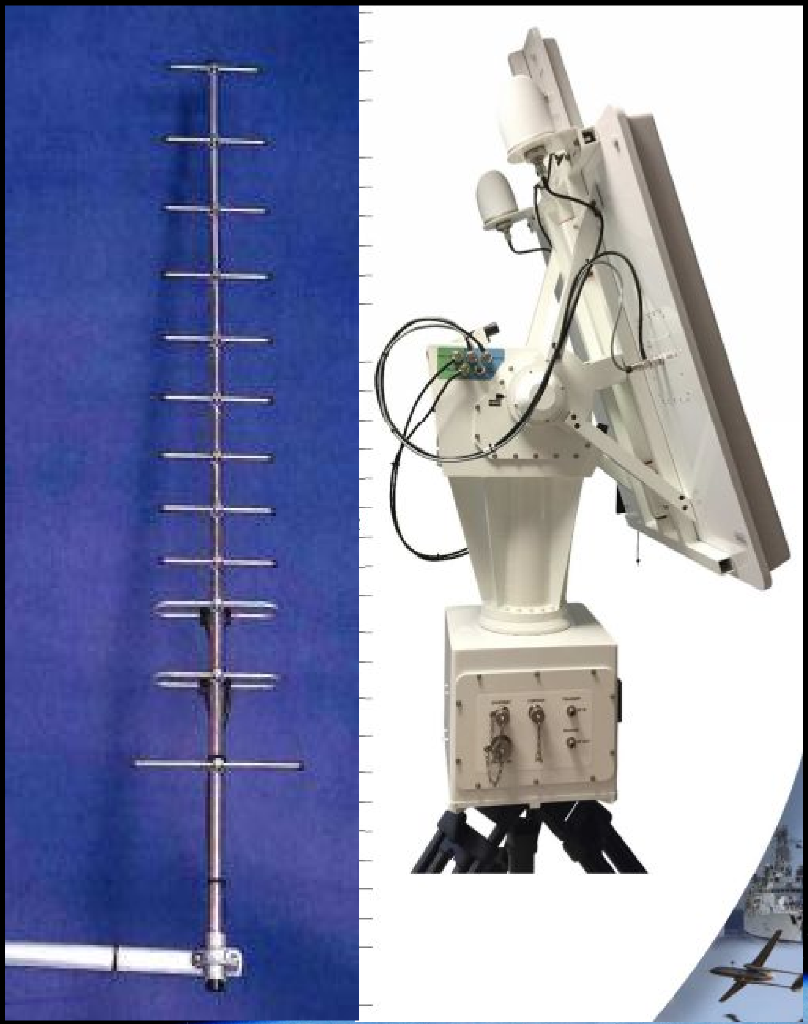
Return to Major Trades

Return to Launch Pad

	Above Ground	Below Ground
Launch Time		
Construction Cost		
Construction Difficulty		
Vehicle Installation Difficulty		
Required Infrastructure		
Durability		

- Below ground construction is more involved and complex. All infrastructure must be more compact.
- Large vehicle is required to install vehicle on either configuration. Below ground may have to be installed in stages or from horizontal position.
- The above ground mechanism requires an alternative protective structure, while the below ground mechanism has to consider how to expel all of the exhaust gases and absorb vibrations.
- Protected from weather by the surrounding ground, unlike an above ground mechanism that is exposed and has to be protected from loading.
- The launch mechanism does not need to be defensible or stealth which are the main characteristics of below ground launch mechanisms.

Ground - LV Communications



- TAS-50 Tracking Device
  - 12 dB Yagi attached
  - Operational in ground wind conditions up to 32 kts
  - Max Elevation Range: -10° to 110°
  - Accuracy: ±0.10°
- Yagi Antenna
  - TRS UHF12DD
  - HPBW: 32°

Note: 2-3 Yagis at each location accounts for elevation angle overlap and risk/reliability

Return to Launch Communications Hardware

Shipping

- Shipping Cost (per container)
  - Land: $3500 across US to East Coast port
  - Land: $100-500 from port to launch pads
  - Land: $25000 for new roads on St. Helena
  - Sea: $10,000 from US port to ports near launch sites
- Total
  - ~$420,000

Launch Sites

LV Storage Trade

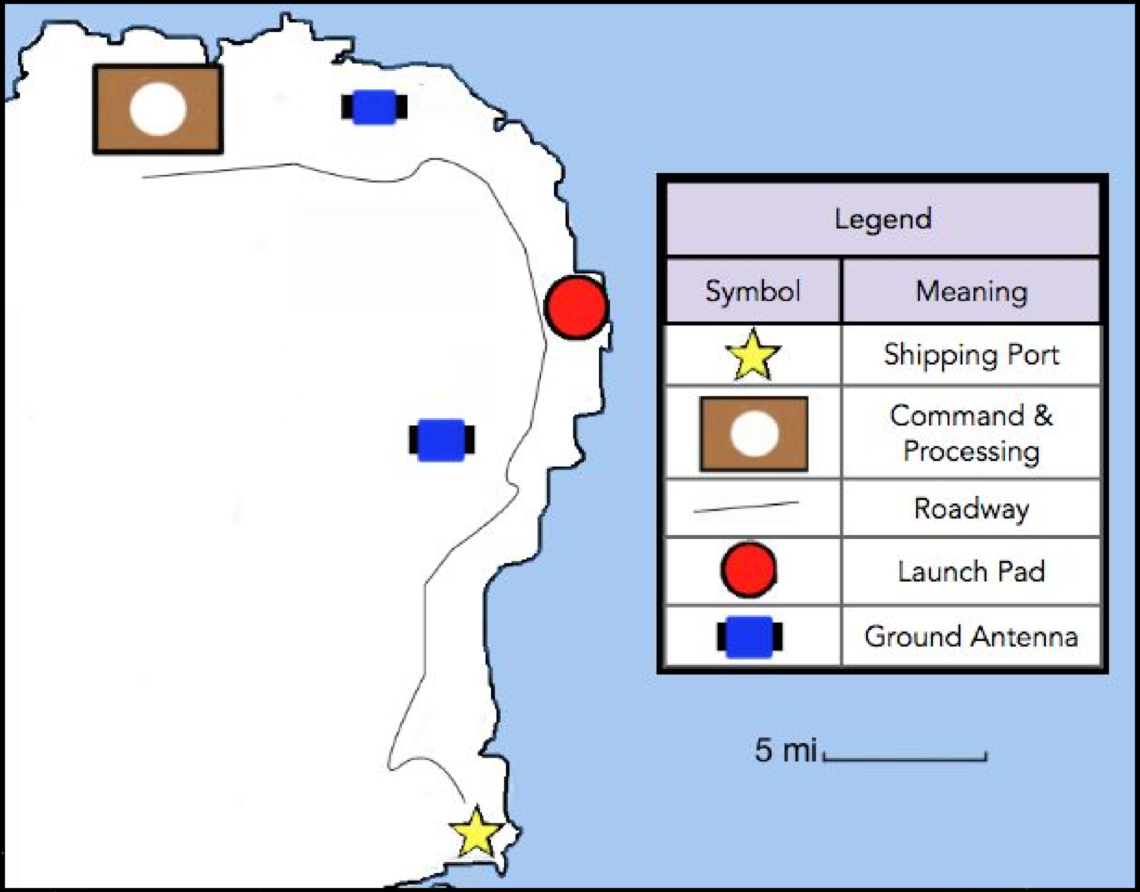
Return to Launch Pad

	Horizontal Storage	Vertical Storage
Integration		
Test/Repair		
Launch Prep Time		
Building infrastructure / Robustness		

Outcome: Horizontal Storage

Launch Sites

Kauai Site Map



Assembly, Integration, and Testing