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SAN LUIS OBISPO

Mission Concept: Emergency Relief Constellation

Presentation Outline

- Mission Objective/Requirements
- Mission-Level Trades
- System Architecture
- Concept of Operations
- Imaging Constellation
- Communications Constellation
- Launch Vehicle

Mission Objective/Requirements

Presenter:
Ian Hughes-Wickham

The Customer

The Humphrey and Prudence Trickelbank 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

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Imaging

- Imaging payload shall 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
    - Above 50 degrees latitude, 15% images not required
- Necessity for thermal infrared (TIR) imaging will be decided by customer on day of launch
    - If TIR imaging is deemed necessary, TIR images of 25% of AOI (determined by customer) shall be taken each day
    - TIR images of AOI require 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-Level Trades

Presenter:
Ian Hughes-Wickham

Mission-Level Trades

- Orbital Altitude
- Satellite Capability Allocation
- Orbit Variability on Day of Launch
- Satellite Distribution Scheme
- Imaging Spectral Band Allocation
- Common Bus

Mission-Level Trades

Orbital Altitude

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

Outcome: **LEO**

Mission-Level Trades

Satellite Capability Allocation

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

Outcome: **Separate Comms and Imaging Satellites**

Mission-Level Trades

Orbit Variability on Day of Launch

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

Outcome: **Variable Orbits**

Mission-Level Trades

Distribution Scheme

	LV Responsible for Burns	Satellite Responsible for Burns
Time Allocated for Distribution		
∆V required		
Number of Maneuvers		
Launch Vehicle Complexity		
Satellite Complexity		

Outcome: **Satellites will Distribute Themselves**

Mission-Level Trades

Imaging Spectral Band Allocation

	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-Level Trades

Common Bus

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

Outcome: **Satellites with a Common Bus**

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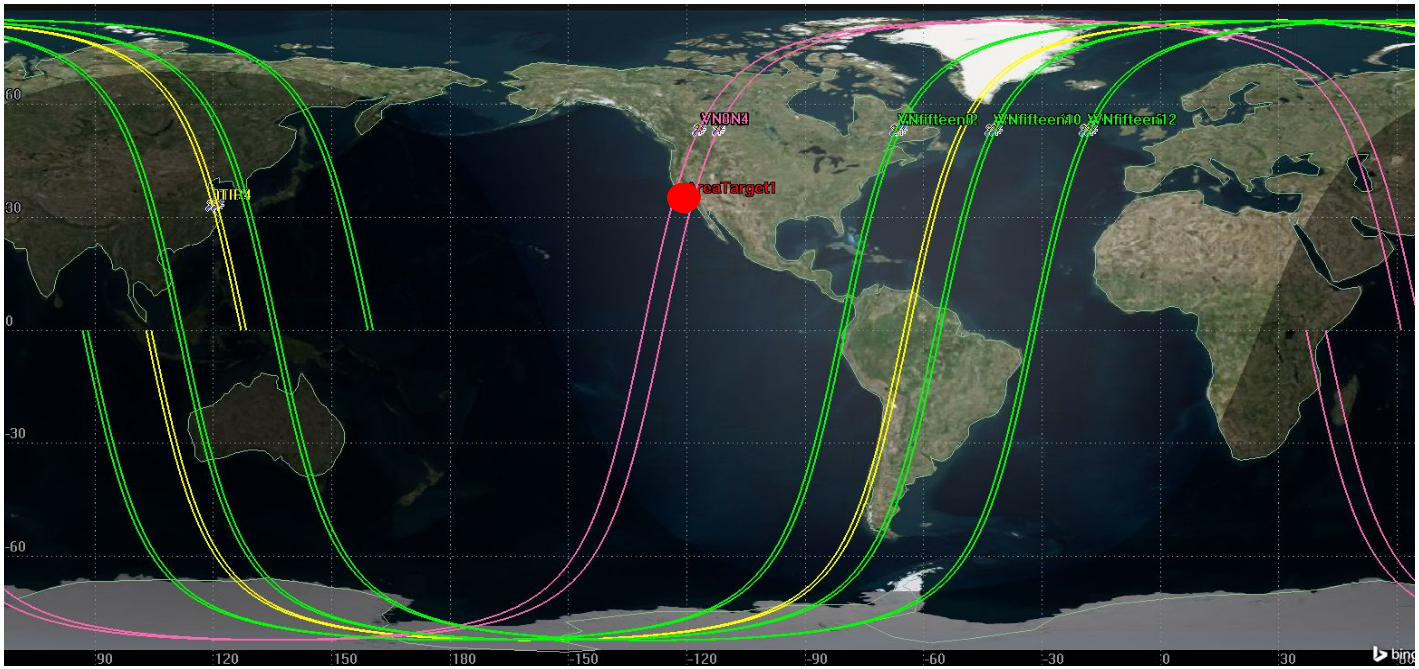
System Architecture

Presenter:

Mazzin Ajamia

Imaging Architecture

Target Area: San Luis Obispo on July 18th, 2017 at 10am



RED = Target Area

PINK = Full Image Vis/NIR

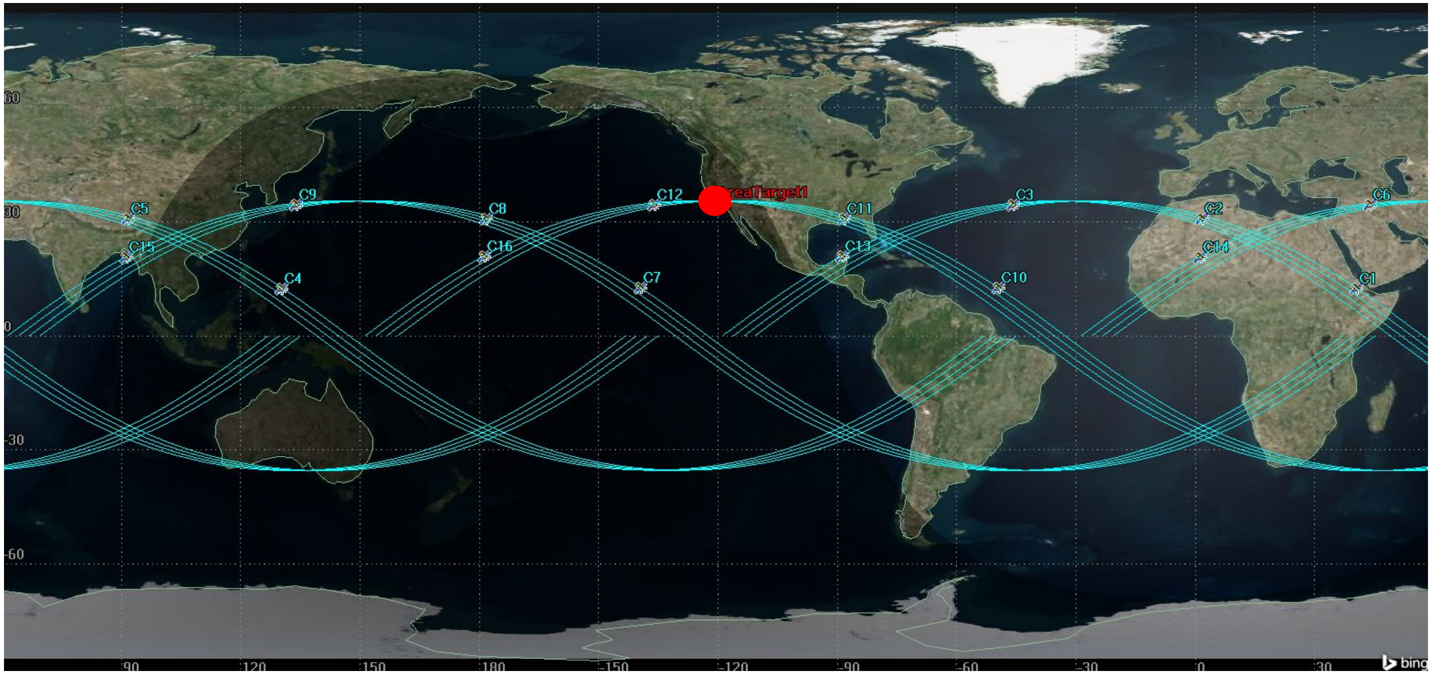
GREEN = 15% Vis/NIR

YELLOW = 25% Image TIR

- **10** planes, **24** satellites
  - **8** sats/full image, Vis/NIR
  - **4** sats/15% image, Vis/NIR
  - **4** sats/25% image TIR
- Circular, **sun-synch 567 km** altitude, **latitude-dependent RAAN spacings**
- Satellite groups dispersed in RAAN
  - Images taken at different times of the day

Communications Architecture

Target Area: San Luis Obispo on July 18th, 2017 at 10am

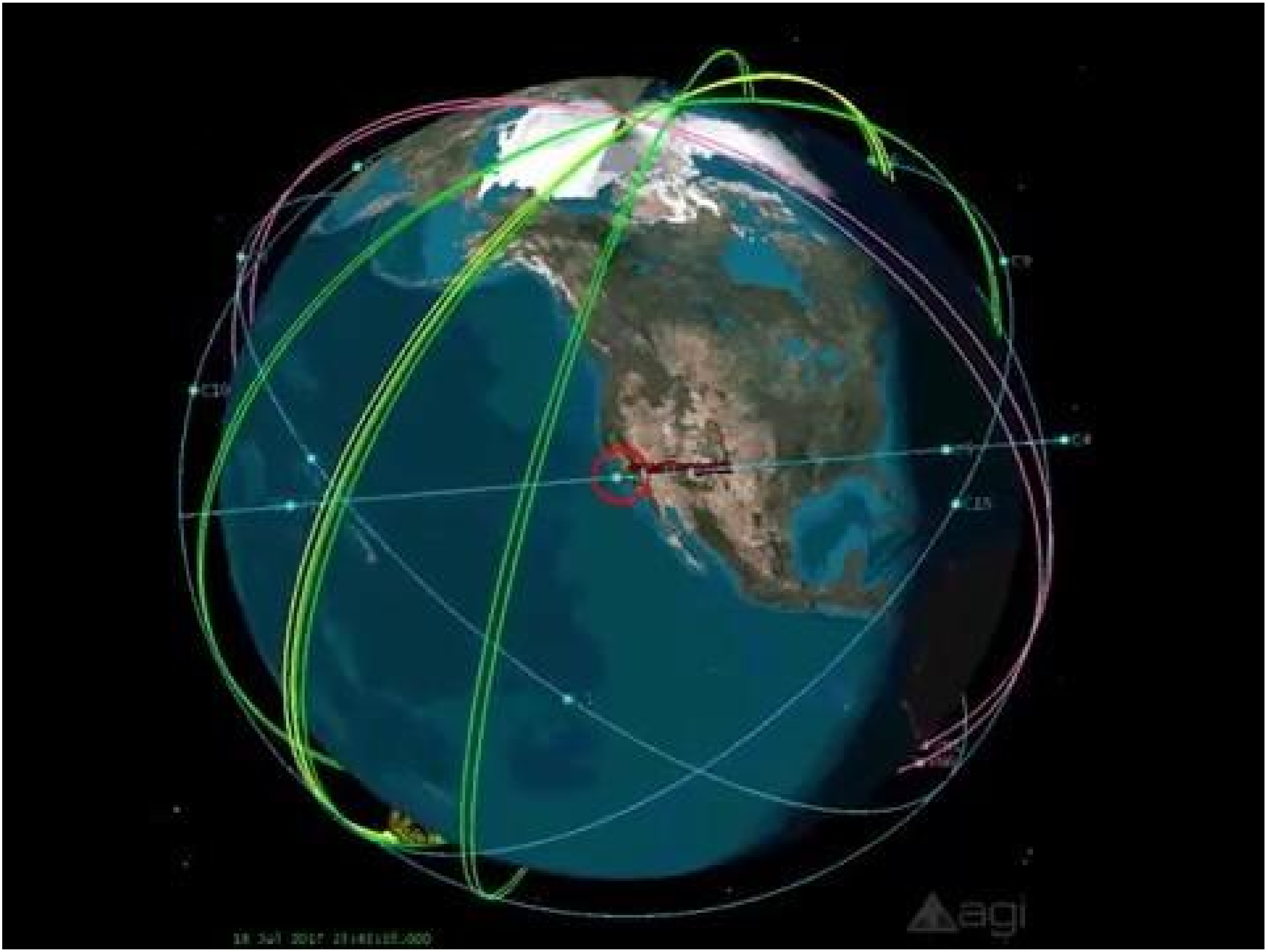


***RED** = Target Area*
***BLUE** = Satellite Ground Tracks*

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

System Visualization

Target Area: San Luis Obispo on July 18th, 2017 at 10am



TOTALS

40 satellites

10 planes

RED ***= Target Area***

PINK ***= Full Image Vis/NIR***

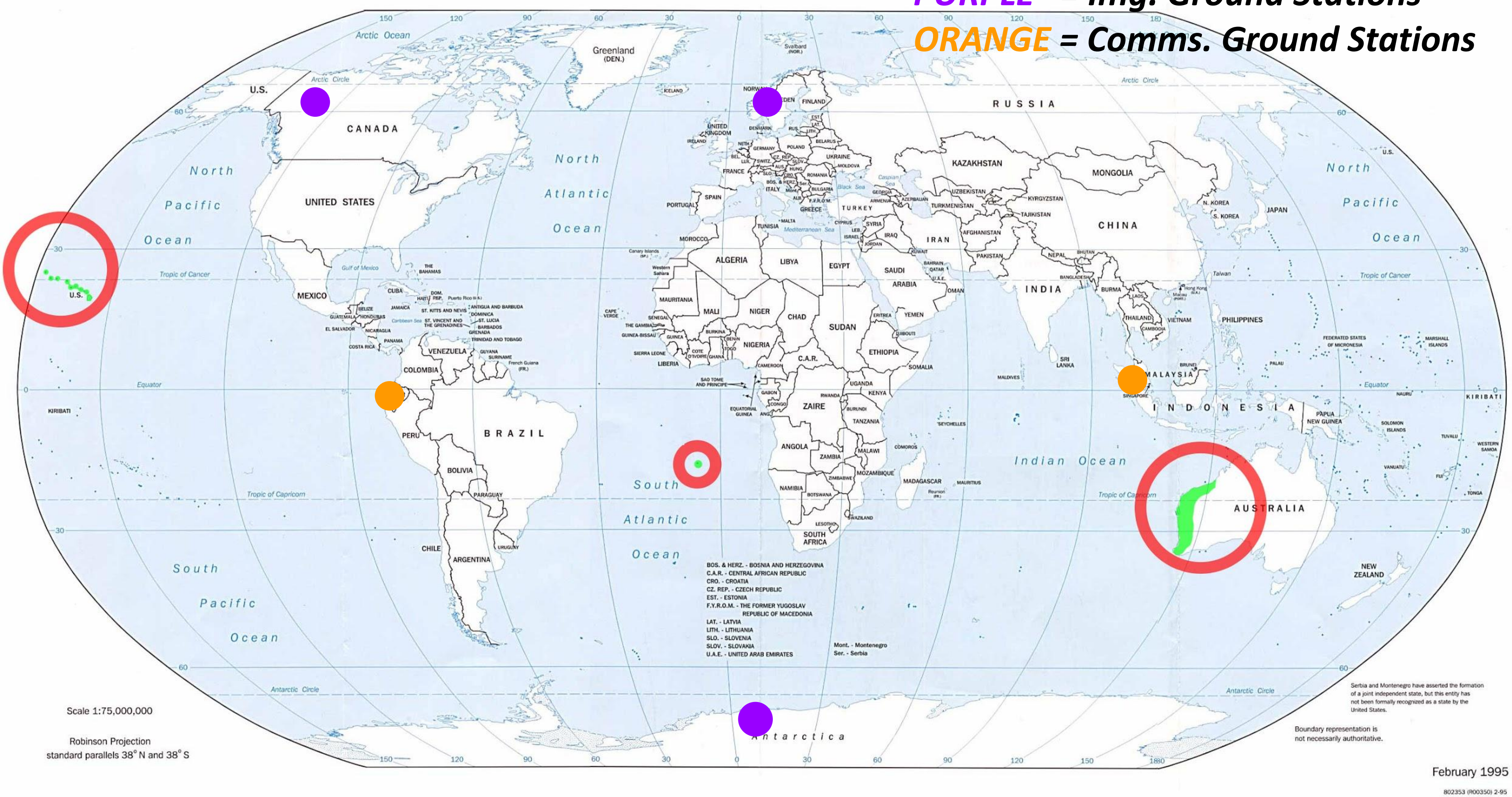
GREEN ***= 15% Vis/NIR***

YELLOW ***= 25% Image TIR***

BLUE ***= Comms. Ground Tracks***

Ground Operations Locations

RED = Launch Sites
PURPLE = Img. Ground Stations
ORANGE = Comms. Ground Stations



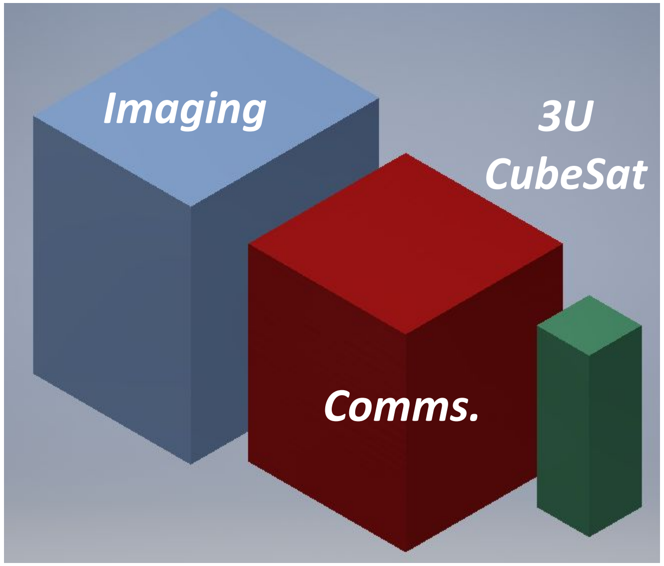
[Slide 122: All Possible Launch Locations](#)

System Summary

Totals

- 40 small satellites
  - 24 imaging satellites in 10 planes
  - 16 communications satellites in 4 planes
- 5 launch sites, 10 launches
- 5 ground stations

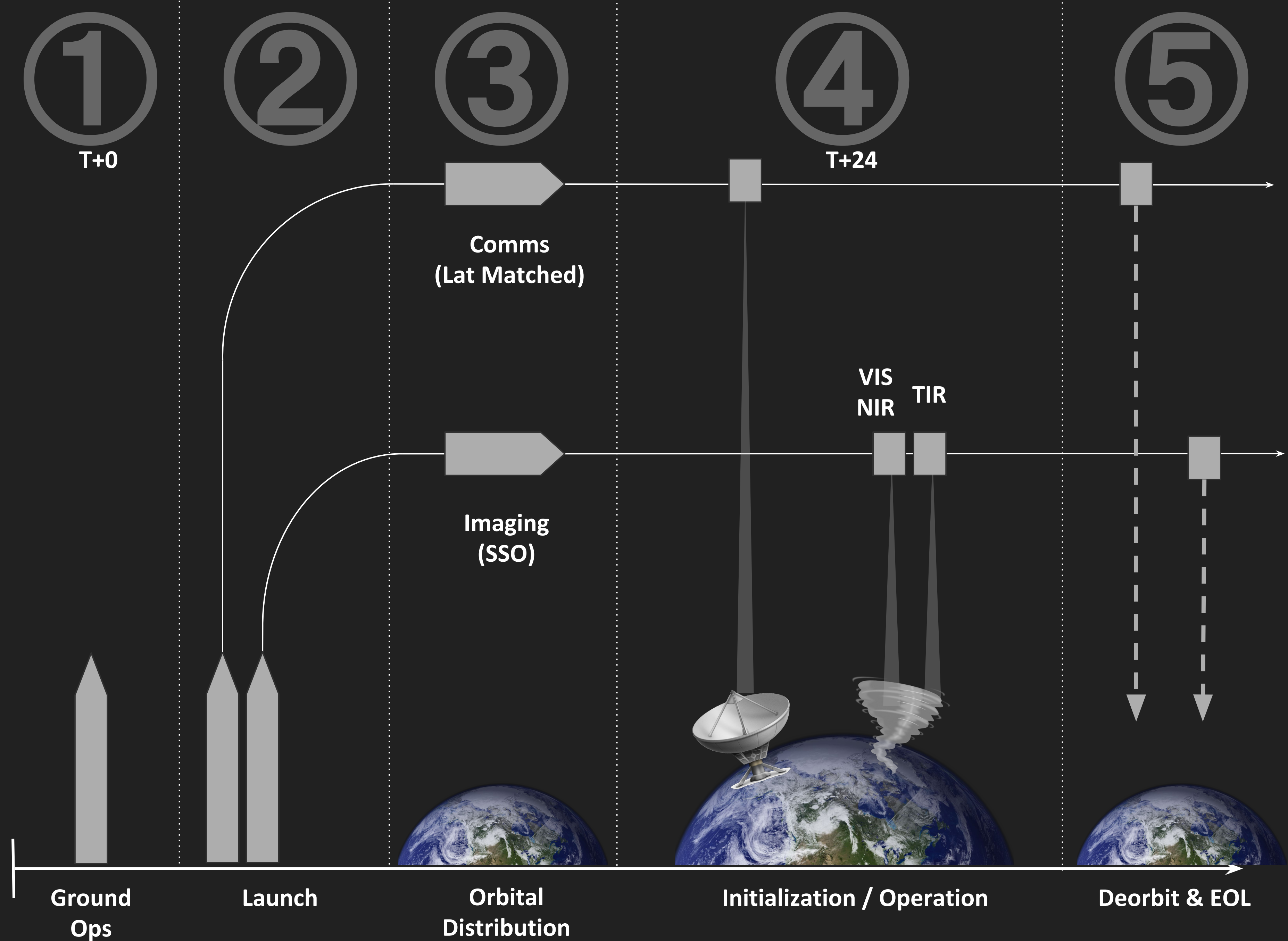
	Imaging Satellites	Communication Satellites
Mass (kg)	10.6	10.2
Dimensions (cm)	30 x 36 x 43	30 x 36 x 30
Volume (cm^3)	46,440	32,400

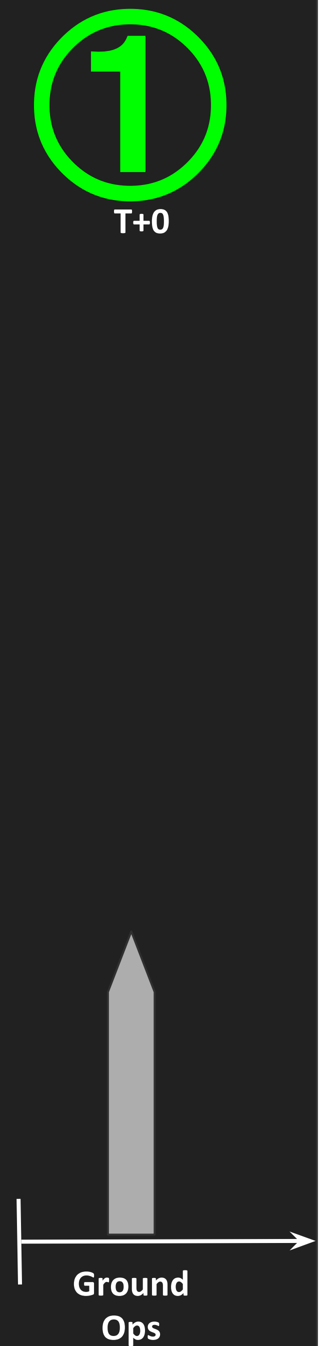


Relative Scale

Concept of Operations

Presenter:
Mazzin Ajamia

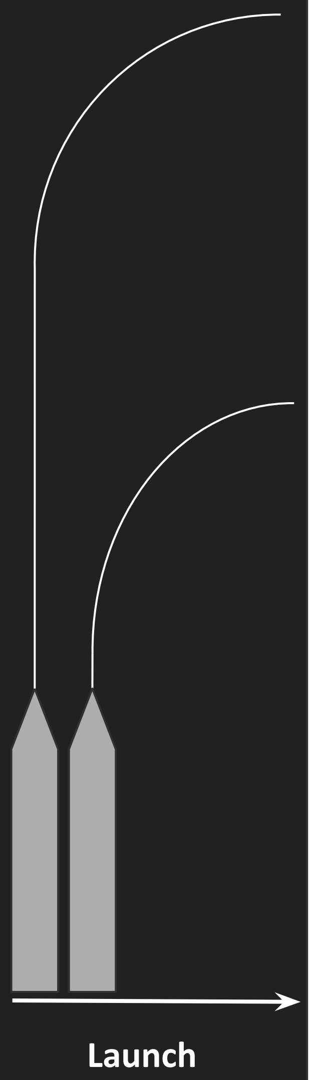

①
②
③
④
⑤
T+0
T+24
Comms
(Lat Matched)
Imaging
(SSO)
VIS
NIR
TIR
Ground
Ops
Launch
Orbital
Distribution
Initialization / Operation
Deorbit & EOL



Pre-Launch Operations

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

②



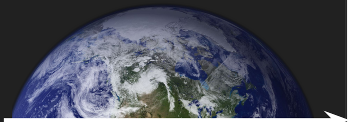
Launch

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

③

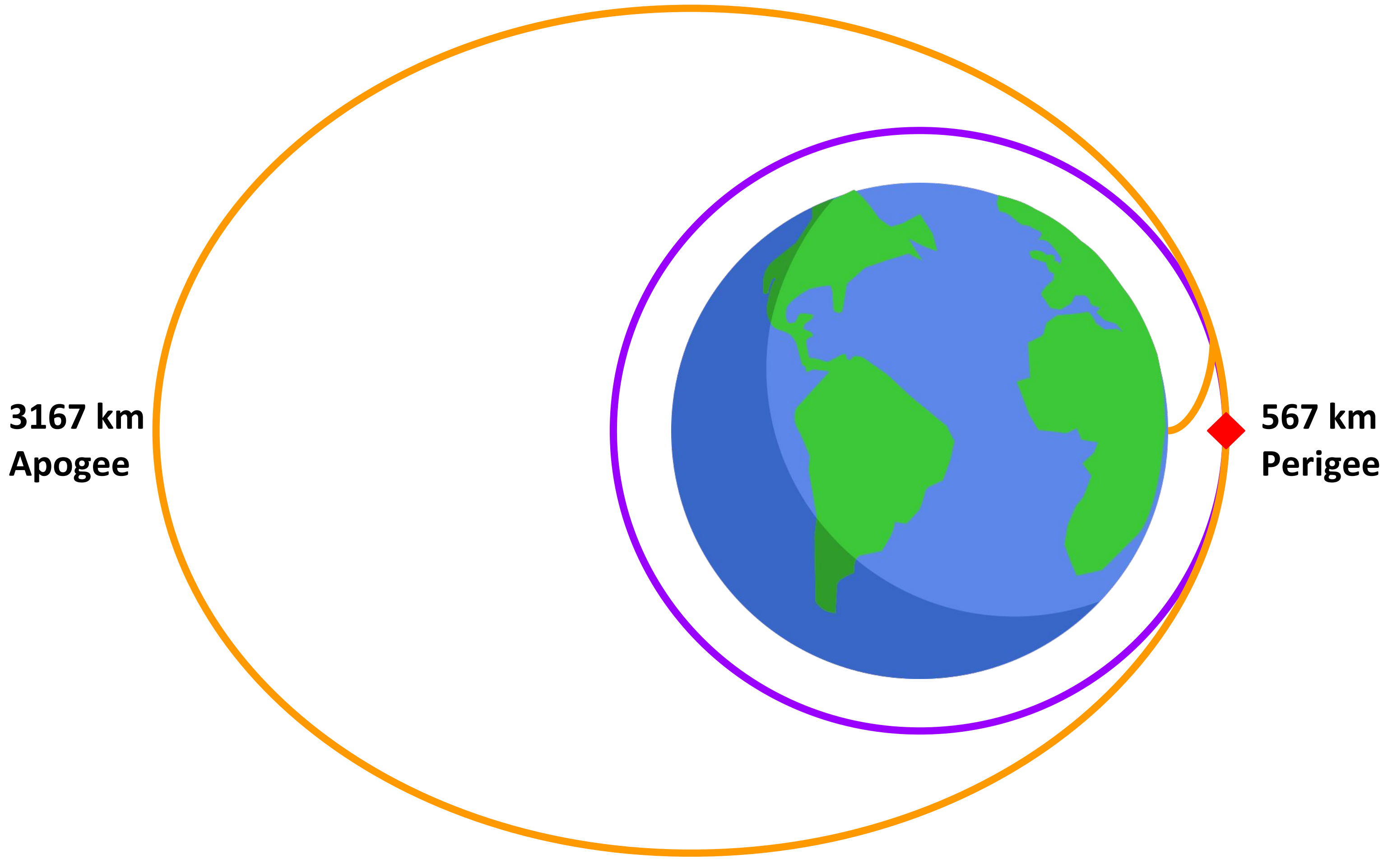
Comms
(Lat Matched)

Imaging
(SSO)



Orbital
Distribution

Orbital Distribution - Imaging



Launch into Phasing Orbit

Final Circular Orbit

Burn Location

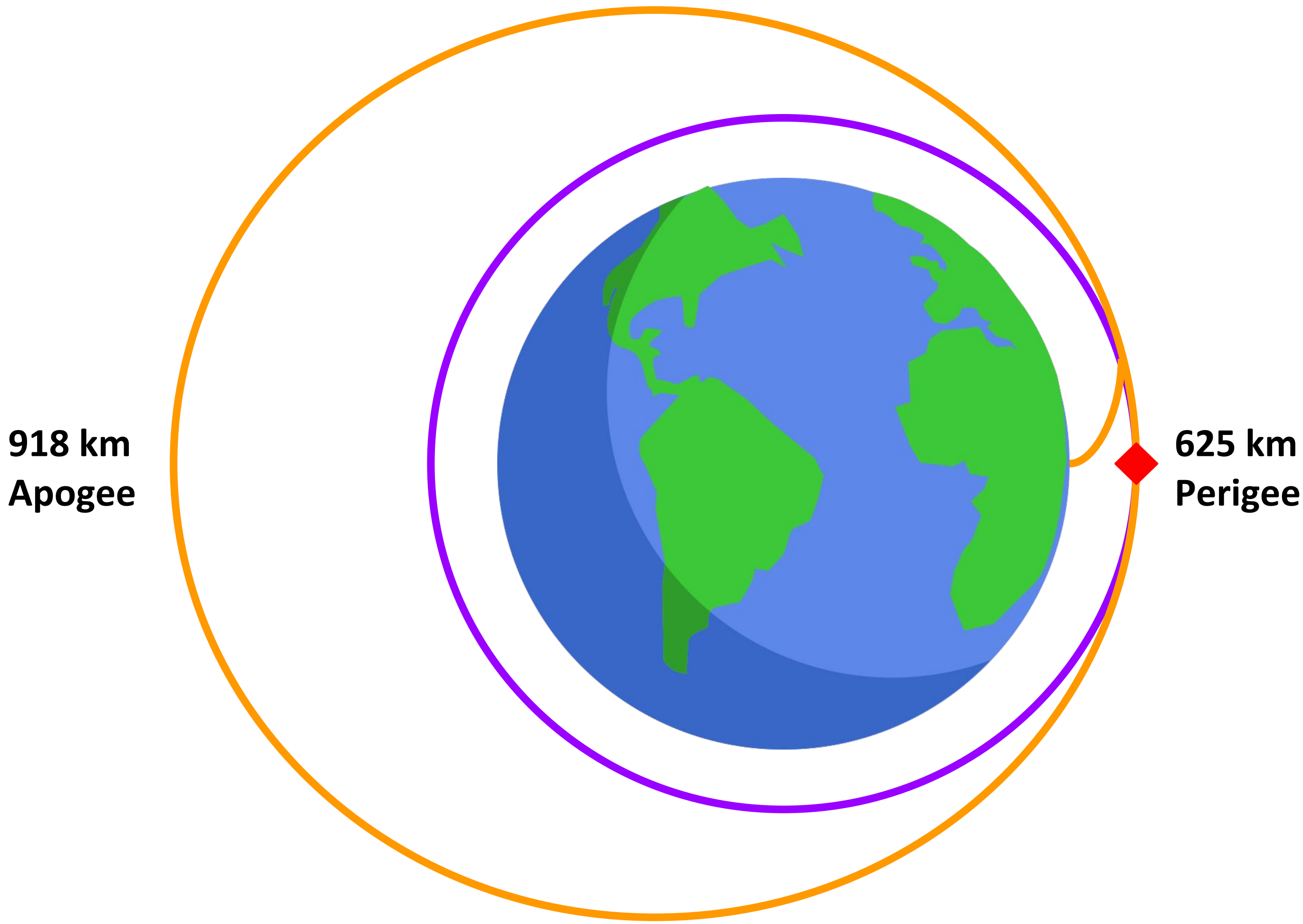
3

Comms
(Lat Matched)

Imaging
(SSO)

Orbital
Distribution

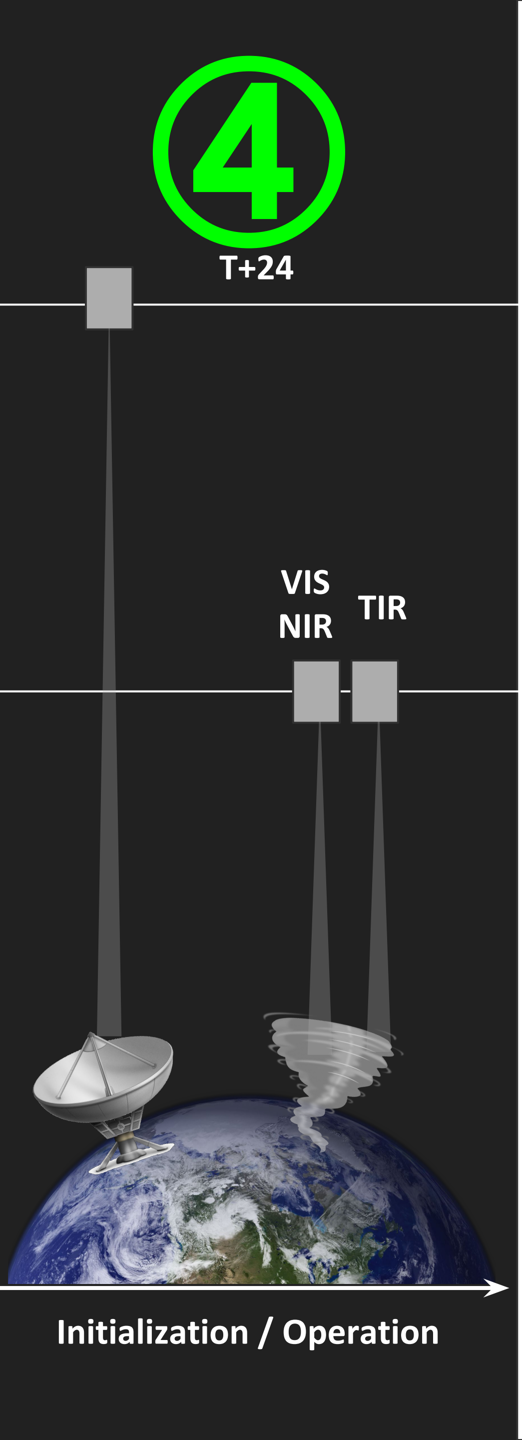
Orbital Distribution - Communications



Launch into Phasing Orbit

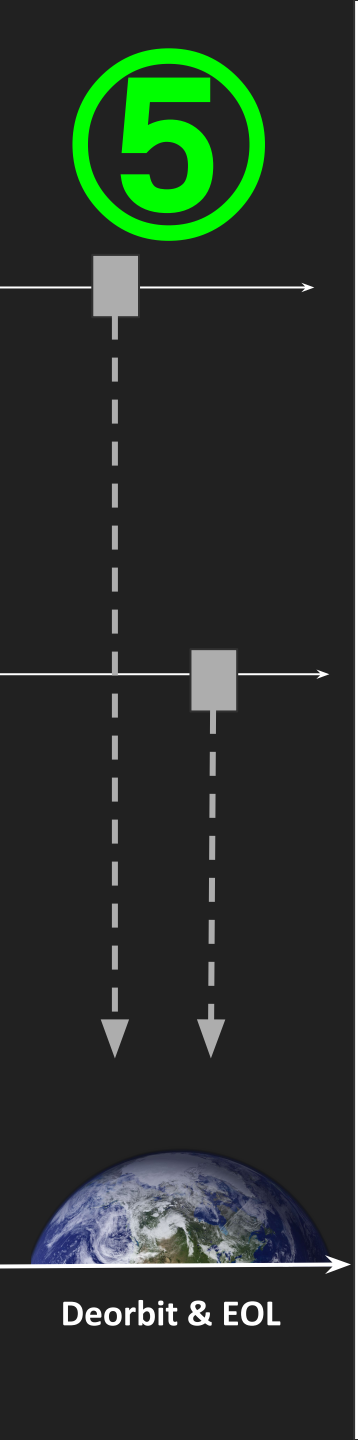
Final Circular Orbit

Burn Location



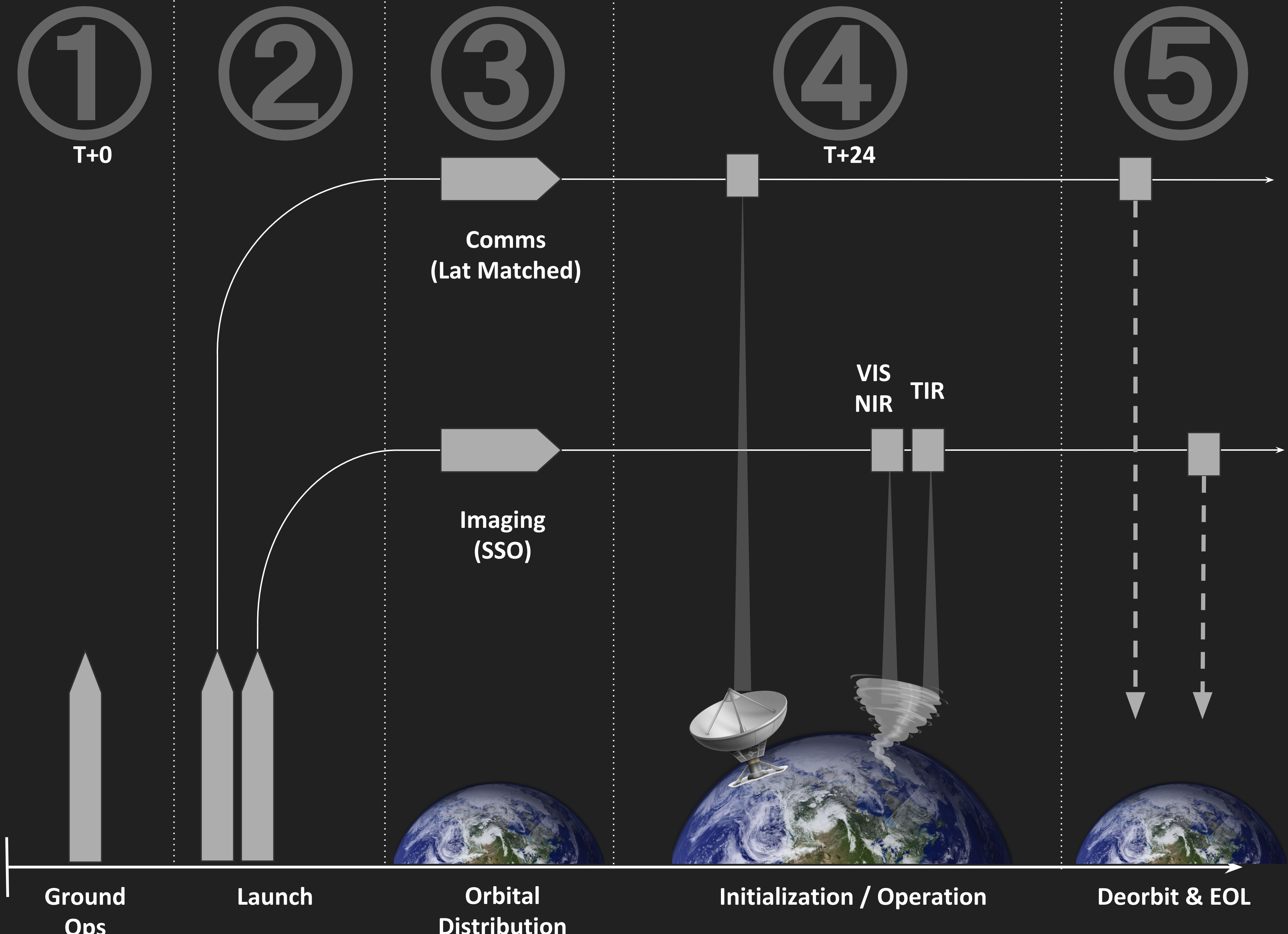
Initialization/Operation

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

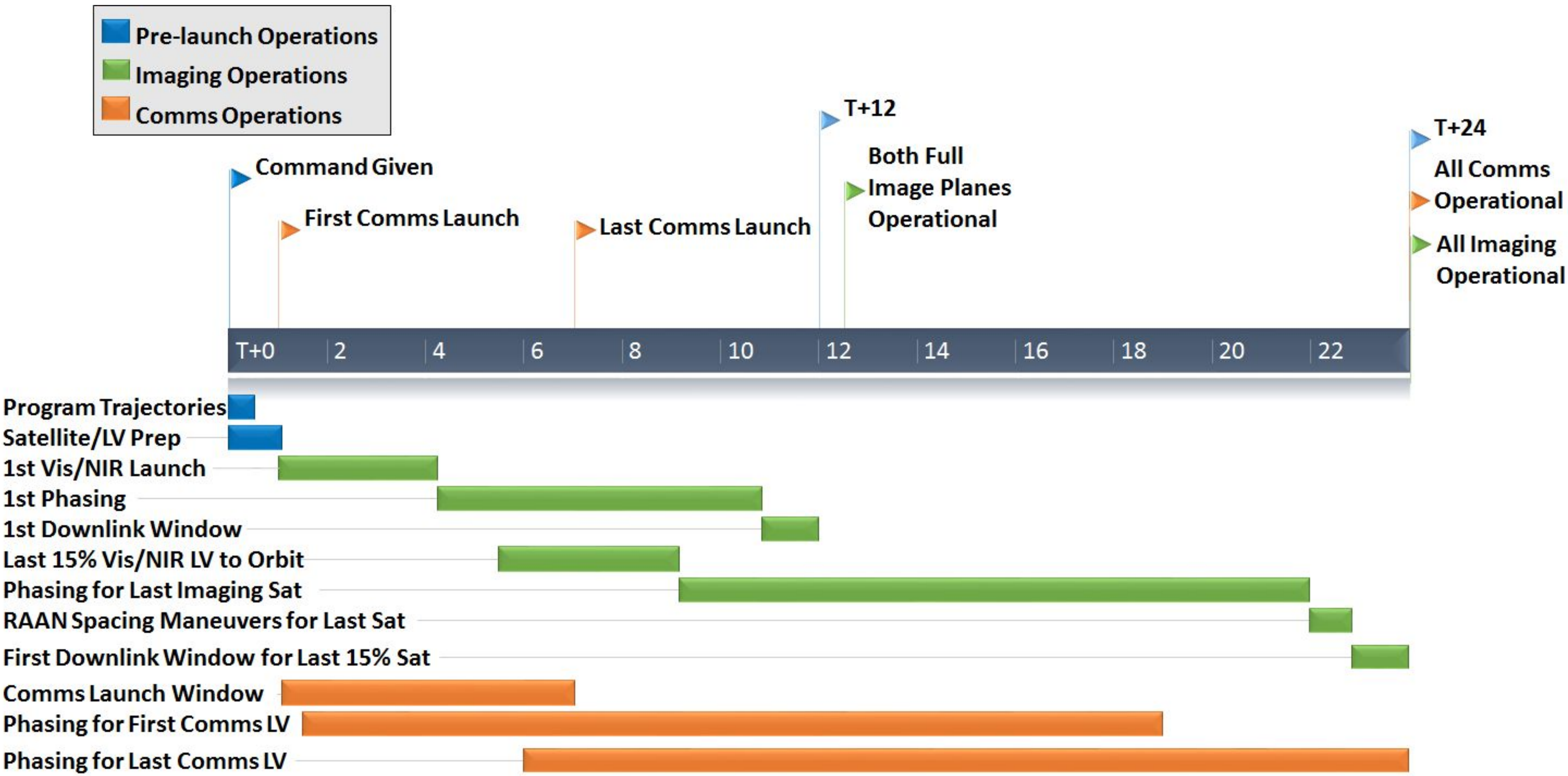


Deorbit & End of Life

- 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

24-Hour Timeline



Imaging Constellation

Presenters:
Nic Cordeniz
David Stears

Imaging Constellation

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Driving Requirements

- Must image Visible (Vis), Near IR (NIR), and Thermal IR bands (TIR)
- Resolution
  - Vis/NIR - 5 m per pixel
  - TIR - 100 m per pixel
- Area of Interest (AOI)
  - Vis/NIR
    - 1 daylight image of entire AOI each day
    - 3 daylight images of 15% squares of AOI
      - Determined daily by customer
      - Not required above 50 degrees latitude
  - TIR (if deemed necessary by customer)
    - up to 25% of AOI composed of a minimum of 5% squares
      - Determined daily by customer

Imaging Constellation

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Major Trades

Trade	Status	Baseline
Orbits	Closed	Sun-sync repeat ground track
Sensor Type	Closed	Pushbroom Scanner
Satellite Capability	Closed	Vis/NIR: 94 km swath TIR: 190 km swath
Planes for Auxiliary Images	Closed	2 Planes
Downlink Antenna	Closed	Ku band horn
ACS	Closed	Cold Gas Thrusters

Imaging Constellation

Orbits Overview

- Full Image Groups (Vis/NIR)
  - 2 planes with 4 sats per plane
  - True Anomaly spaced (max 6.5 km separation between first and last satellite in the sky)
  - Other orbital parameters determined by target area

- 15% Groups (Vis/NIR) and 25% Group (TIR)
  - 2 planes with 2 sats per plane
  - True Anomaly spaced sats (max 6.5 km separation)
  - Other orbital parameters determined by target area
  - Three groups total to take three 15% images
    - Groups RAAN spaced to provide time between images (customer requirement)

Imaging Constellation

Orbital Scheme: Visible/NIR

Latitude	0° - 50°	50° - 80°	80° - 90°
Orbit Type	Sun-Synchronous Repeat Ground Track		Polar Repeat Ground Track
Altitude	567 km		554 km
Inclination	97.7°		88.4° and 91.6°
No. of Planes	8	2	2
Total No. of Satellites	20	8	8

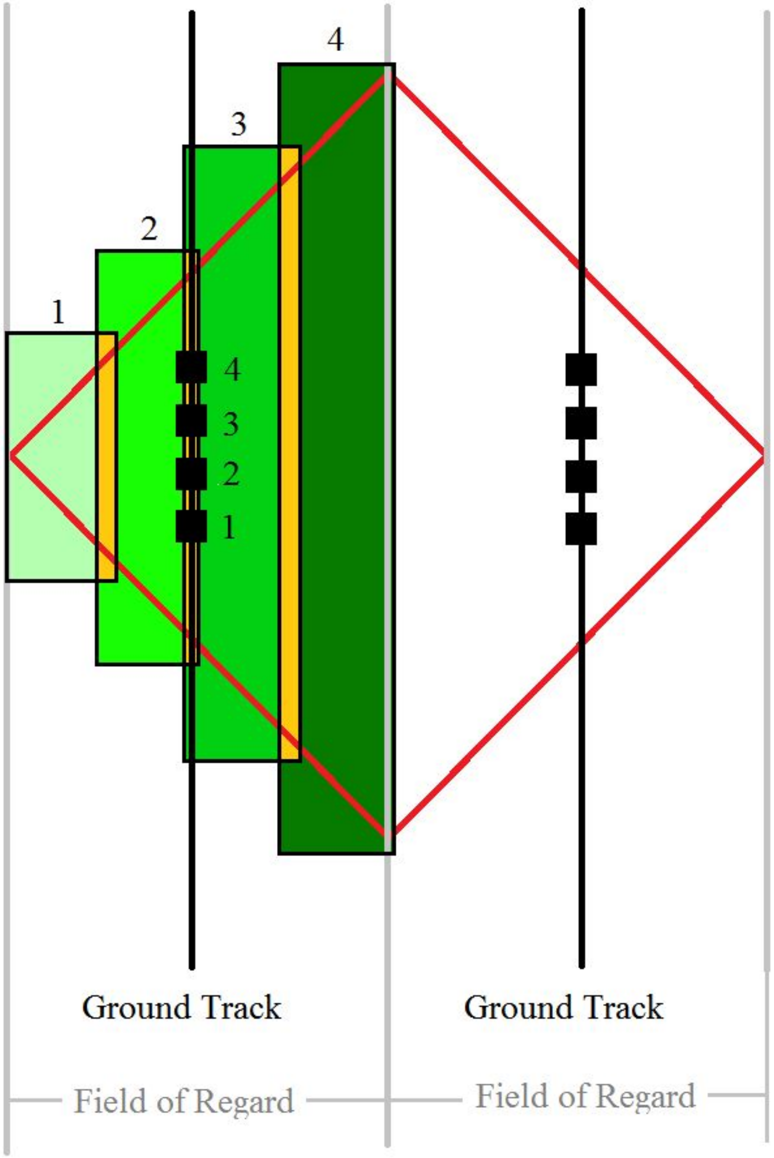
Imaging Constellation

Vis/NIR Imaging Scheme

Pushbroom Scanner

Entire AOI Groups:

- Max off-nadir slew: 11.3 deg
- Swath width: 94 km
- Overlap: 3% between swaths
- Separate launches for each plane



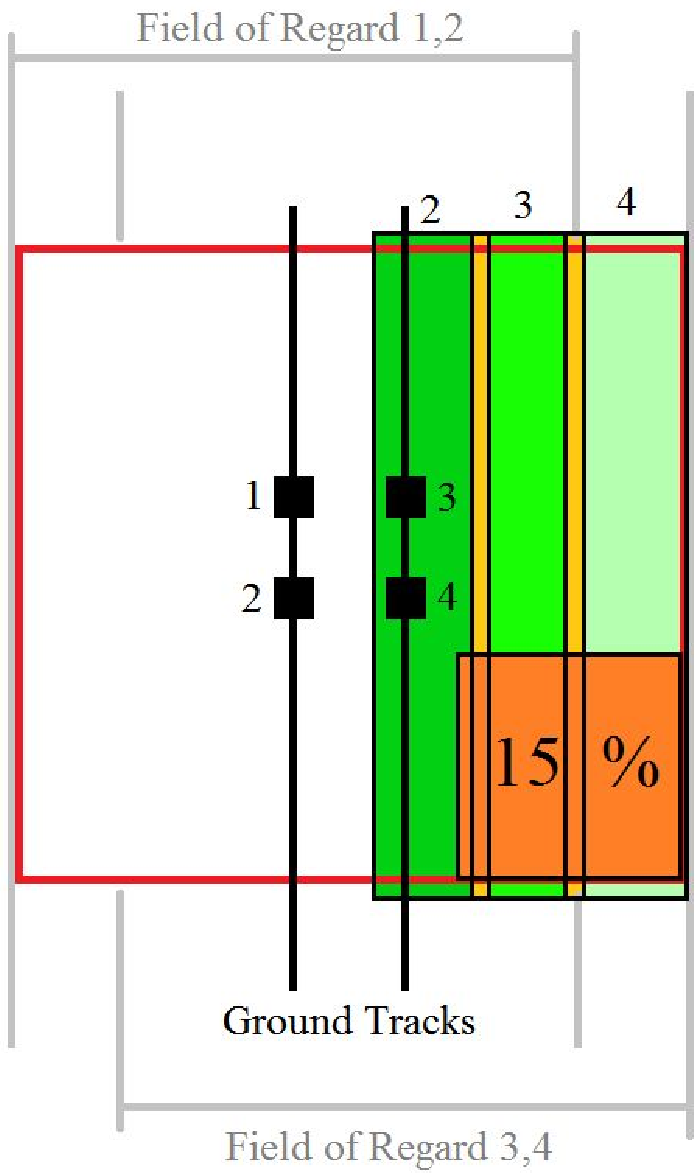
Imaging Constellation

VIS/NIR Imaging Scheme

Pushbroom Scanner

15% Groups:

- Max off-nadir slew: 18 deg
- Swath width: 94 km
- Overlap: 3% between swaths



Imaging Constellation

Orbital Scheme: Thermal IR

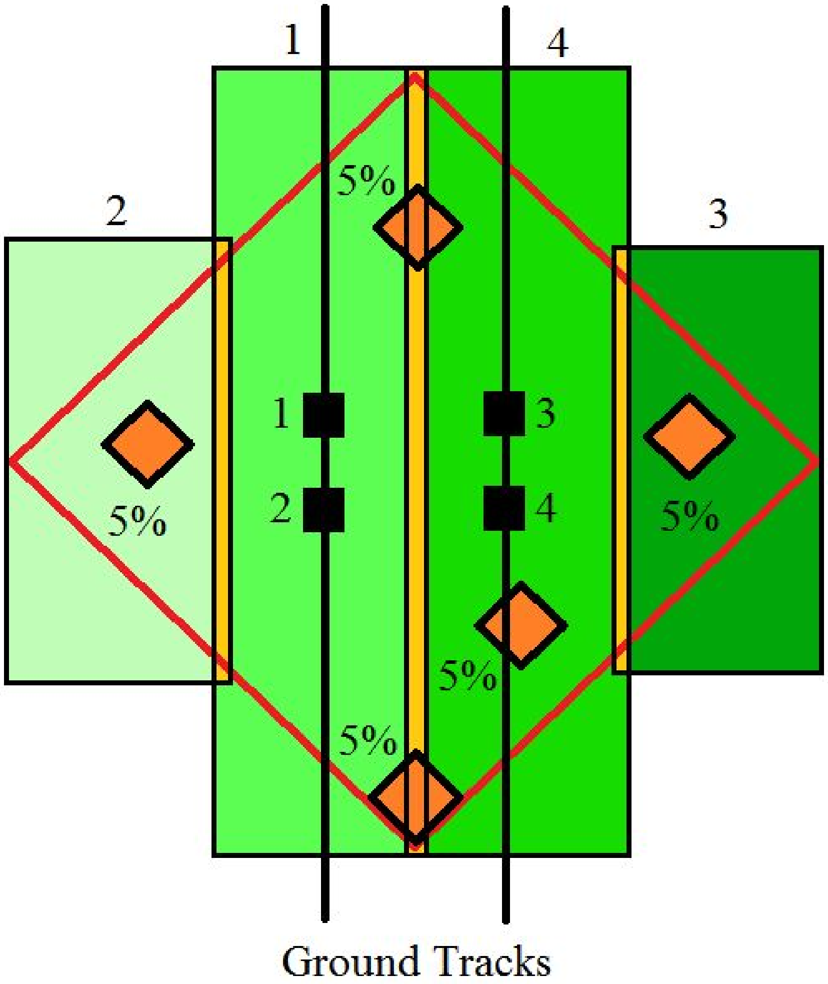
Latitude	0° - 80°	> 80°
Orbit Type	Sun-Synchronous Repeat Ground Track	Polar Repeat Ground Track
Altitude	567 km	554 km
Inclination	97.7°	88.4° and 91.6°
No. of Planes	2	
Total No. of Satellites	4	

Imaging Constellation

TIR Imaging Scheme

Pushbroom Scanner

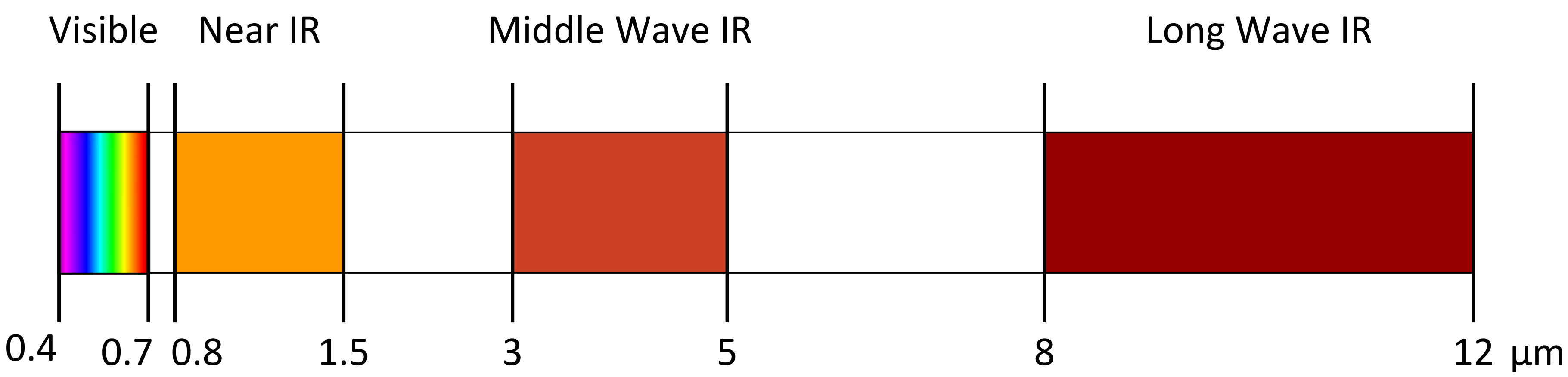
- Max off-nadir slew: 19 deg
- Swath width: 190 km
- Planes RAAN spaced
- Overlap: 3% between swaths
- 25% could be in as many as five 5% areas
- Providing more capability than required



Imaging Constellation

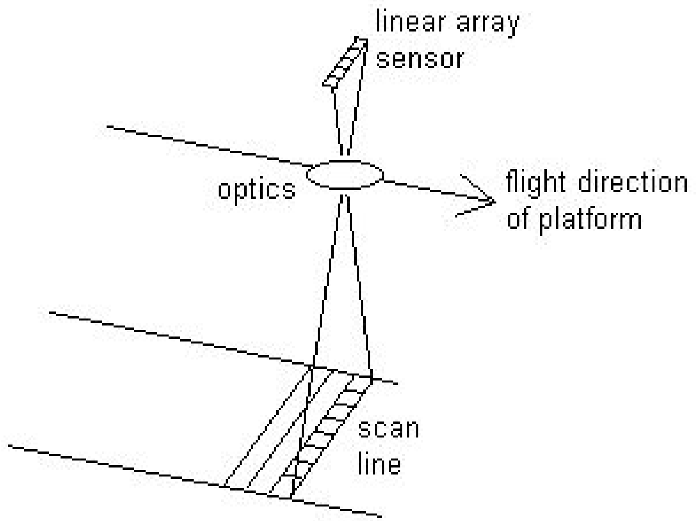
Spectral Bands of Interest

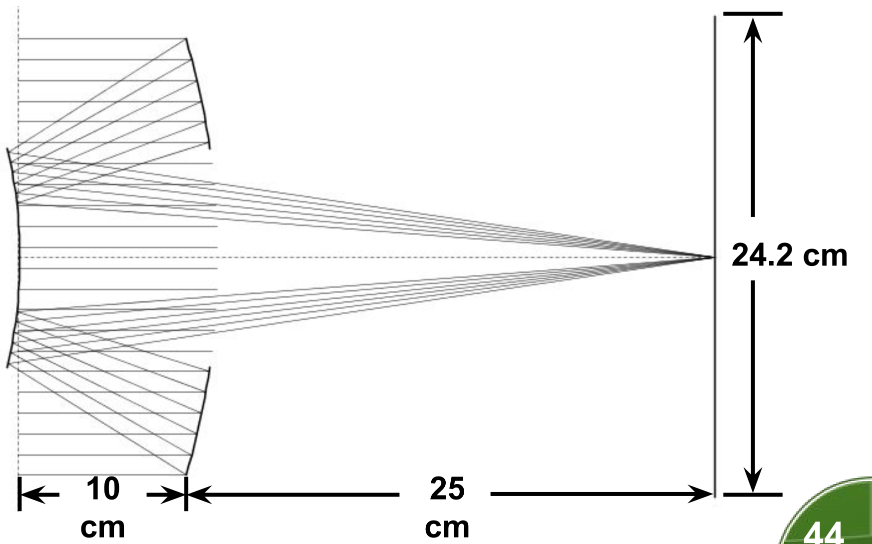
- Visible
  - 0.4-0.7 µm
- Near IR
  - 0.8-1.5 µm
- Middle Wave IR
  - 3-5 µm
- Long Wave IR
  - 8-12 µm



Optical Payload

- Pushbroom sensor
  - Linear sensor array
- Reflecting telescope
  - Cassegrain design
  - Same optics for both Vis/NIR and TIR
  - ∅25cm x 36.5cm allocated space
- Number of Detector Elements
  - Vis/NIR: 22,000 x 6 bands
  - TIR: 4,300 x 6 bands

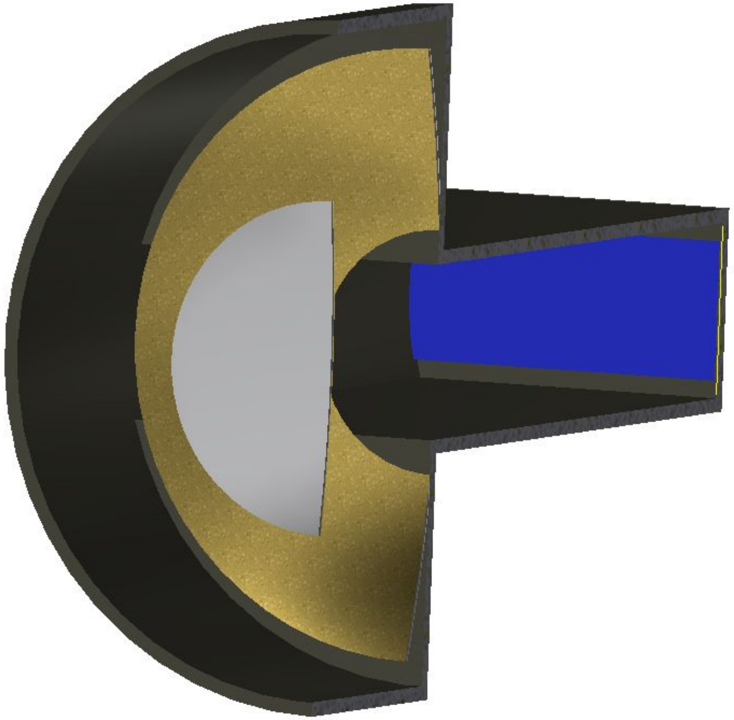




Imaging Constellation

Optical Payload

- 22 cm diameter primary mirror
- 12 cm diameter secondary mirror
- 12.2 cm VIS/NIR Optical Sensor
- 24.2 cm TIR Optical Sensor



Optical Sensor Cross-Section View

[Slide 127: Optics Light Capture - Secondary View]

Imaging Constellation

Image Data

- Vis/NIR Full Image:
  - Uncompressed Data Volume: 30 GB
- Vis/NIR 15% Images:
  - Uncompressed Data Volume: 8 GB
- TIR 25% Images:
  - Uncompressed Data Volume: 0.32 GB
    - Based on 45 m per pixel resolution
- 2:1 compression algorithm used on all images to be downlinked to ground stations

Imaging Constellation

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Imaging Satellite Communications

- On-board system for downlinking:
  - Ku-Band
  - Wideband horn, 4.3 x 5.2 x 11.2 cm
  - BPSK modulation
- Ground system for downlinking:
  - 2.3 m ground dish to downlink all satellites
  - 48 dB peak gain

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	400 Mbps
Gain	14 dB
Power (RF)	20 W
Margin	4.3 dB

Imaging Constellation

Imaging Satellite Communications

- On-board system for TT&C:
  - UHF Band
  - Four whips in phase quadrature, 18 cm length
    - Common TT&C system to comms satellite
  - BPSK modulation
- Ground system for TT&C:
  - Utilizing same ground dish for imaging downlink and TT&C
    - 14.7 dB peak gain for UHF using the same ground dish

TT&C Link Budget	Downlink	Uplink
Frequency	300 MHz	
Noise Temp	285 K	
Space Loss	146 dB	
Signal to Noise Ratio	10.5 dB	
Data Rate	9.6 kbit/s	
Gain	0 dB	14.7 dB
Power (RF)	0.25 W	0.25 W
Margin	16 dB	

Imaging Constellation

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Propulsion System

- SSC: High Performance Green Propellant System
  Propellant: LMP-103S
  - F = 5 N of directed thrust
  - ISP = 250 s
  - Compact Combustion Chamber and Nozzle
    - Diam ~ 3 cm
    - Length ~ 8 cm

17.8 cm

Source: 2013 ECAPS

Engine Decision

Imaging Constellation

Satellite Maneuvers Summary

- On-orbit station-keeping
- De-orbit in 5 years after 6 month lifetime
- ΔV budget

Maneuver	**Phasing**	**Stationkeeping**	**De-Orbit**	**Total**
Required ΔV	575 m/s	75 m/s	50 m/s	**700 m/s**

Slide 119: Liquid Monopropellant Trade

ADCS: Attitude Determination

- Sensors:
  - Star tracker - 3-axis attitude knowledge
  - 3 Sun Sensors - 2-axis attitude knowledge
- Attitude knowledge requirement: 0.03 degrees
  - Derived from 0.3 degree pointing requirement (industry standard)
- Fine knowledge required during imaging phase only
  - Star tracker falls out of attitude knowledge requirements at ~1.1 deg/sec

Imaging Constellation

ADCS: Control

- 8 - Nozzle ACS Thruster Configuration
  - MOOG SVT01 10 - 50mN Nitrogen Cold Gas thrusters
  - On opposing faces
- Pointing requirements derived from payload swath width

	Imaging	**Downlink**	**Sun-Tracking**
Pointing Requirement (deg)	0.3	7.5	25
Slew Rate (deg/s)	0.003	0.5	0.003

MOOG Thruster Specs

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ADCS: Pointing Budget

	Source	X-Axis & Y-Axis [deg]	Z-Axis [deg] (Through Optics)
System	Thermal Error	3e-3	3e-3
Environment	Thermal Deformation	3.7e-3	2.4e-3
AD Sensors	Star Tracker Accuracy	5.5e-3	2.78e-3
	Star Tracker Misalignment	2.0e-5	2.0e-5
	Gyro Misalignment	5.7e-2	5.7e-2
	Gyro Angular Random Walk (max)	1.1e-3	1.1e-3
	Gyro Scale Factor Error	5.1e-6	1.5e-5
Actuator	RCS Thruster Misalignment	2.0e-5	2.0e-5
Main Thruster	Thruster Misalignment	2.0e-5	2.0e-5
Guidance	GPS Position Accuracy	8.97e-6	8.2e-11
	Clock Error	1.8e-10	1.8e-10
	Total RSS Error (with 25% Contingency)	**0.0722**	**0.0718**

Imaging Constellation

Mass Breakdown:

Subsystem	Mass (kg)	Percent of Total
ADCS	0.91	7
Propulsion	2.3	22
Structure	1.4	14
Thermal	0.1	1
Imaging Payload	3	29
Comms	0.18	1.7
TT&C	0.50	4.8
Power	2.2	21
Total	**10.6**	100

Mass-Power-Thermal

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Thermal Considerations:

- High output during payload operation and downlinking
- Phase change materials
- Cold biasing
- Moving Forward:
  - Transient analysis
  - Optimize configuration

Component(s)	Temperature Range, °C
Most Components	-40 to 80
Main Propellant	-5 to 50
RCS/ACS Propellant	0 to 50
Vis/NIR Payload	0 to 65
TIR Payload	Less than 57

Imaging Constellation

Power Cycle (Operations Timeline)

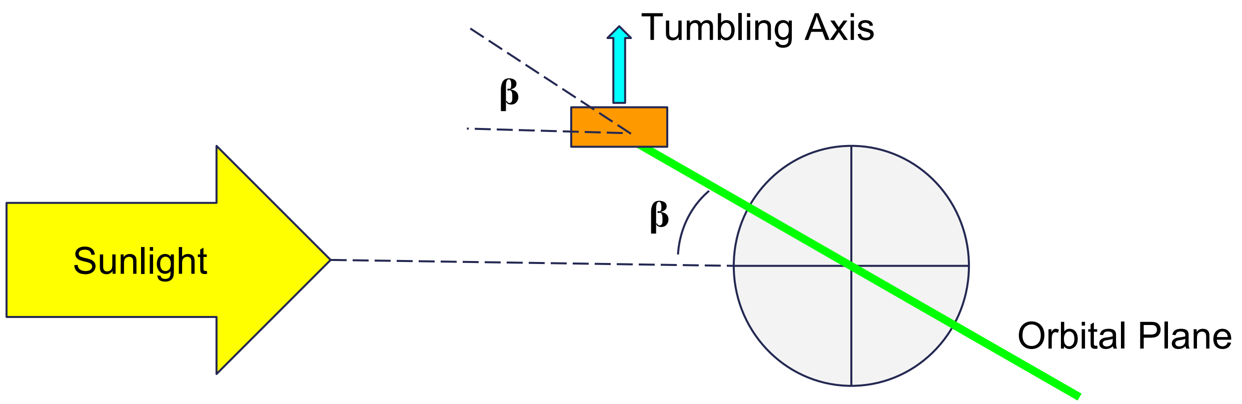
- Each satellite orbits 15 times per day
    - 1 orbit includes image collection and processing
    - 1 orbit includes image downlink and orbit maintenance
    - Other 13 orbits devoted to recharging the batteries
    - Worst case power mode grouping if target area positioned such that downlinking occurs immediately following image processing. ~ 26 Wh battery usage prior to recharge.

Battery and Solar Panel Sizing

Imaging Constellation

Power Cycle (Operations timeline)

- Average power required: 4.5 W (per 1 day cycle)
- Peak Power: 180W (calibration and imaging)
- 3 Body-mounted solar panels
- 40 Whr of battery storage
- Tumbles at fixed angle offset depending on orbital plane



View Factors

Imaging Constellation

Power Cycle (Operations Timeline)

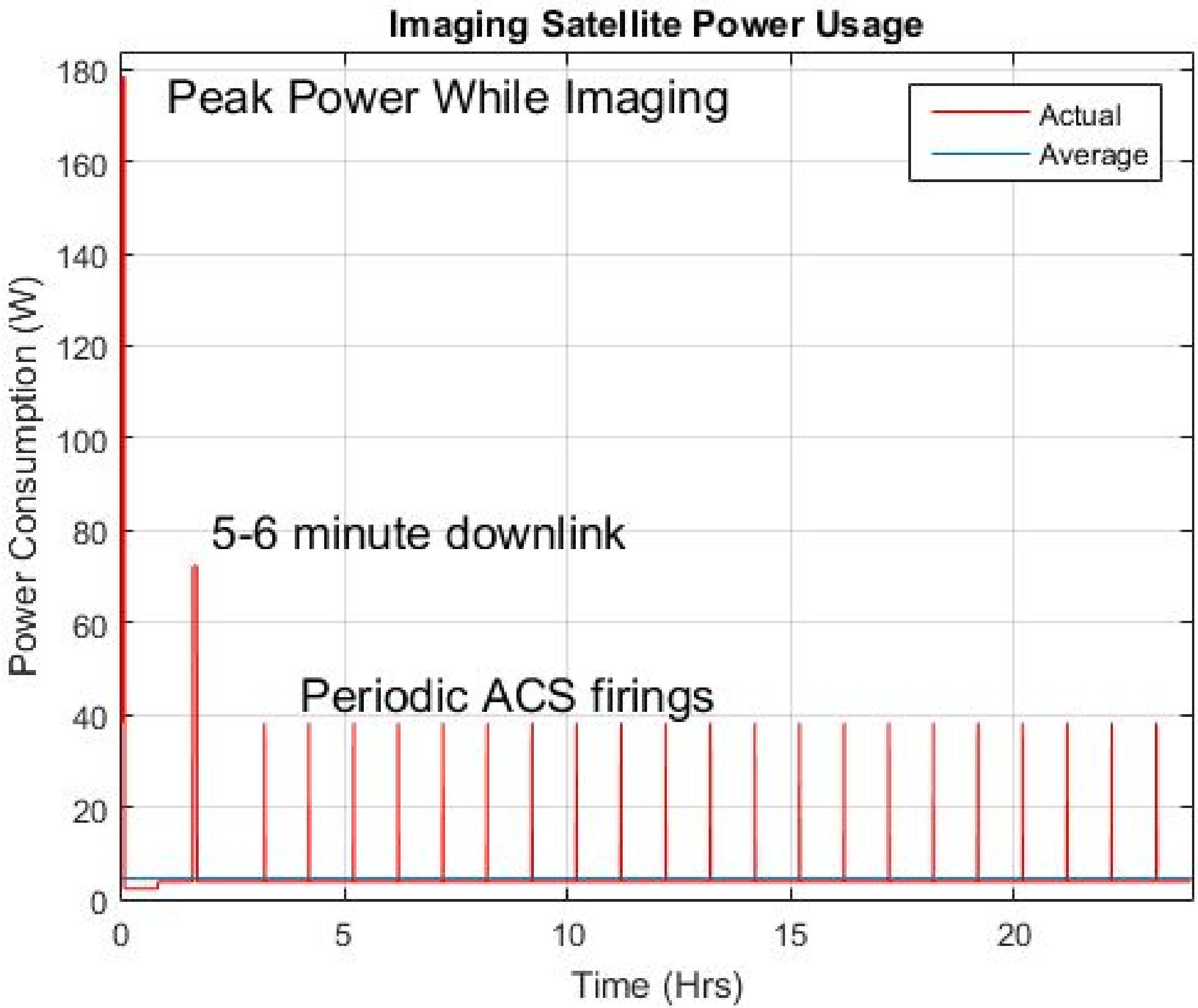
Daily Cycle Consumes 105 Wh of Energy

	Payload Operational Orbit		Ground Station Fly Over Orbit		Remaining 13 Orbits	
Tasks and Corresponding Energy Required	**Pointing, Calibrating, and Imaging**	**10 Wh**	**Pointing, Downlinking, and TT&C**	**6.8 Wh**	**Standby Operations**	**6 Wh each**
	Compress Image	**2 Wh**	**Correct Orbit**	**0.2 Wh**		
	Standby Operations	**3 Wh**	**Standby Operations**	**5.5 Wh**		
	Totals	**15 Wh**		**12.5 Wh**		**78 Wh**

Note: Placement of these orbits in the daily schedule depends on target location, ground station location, and time the customer determines that pictures are to be taken.

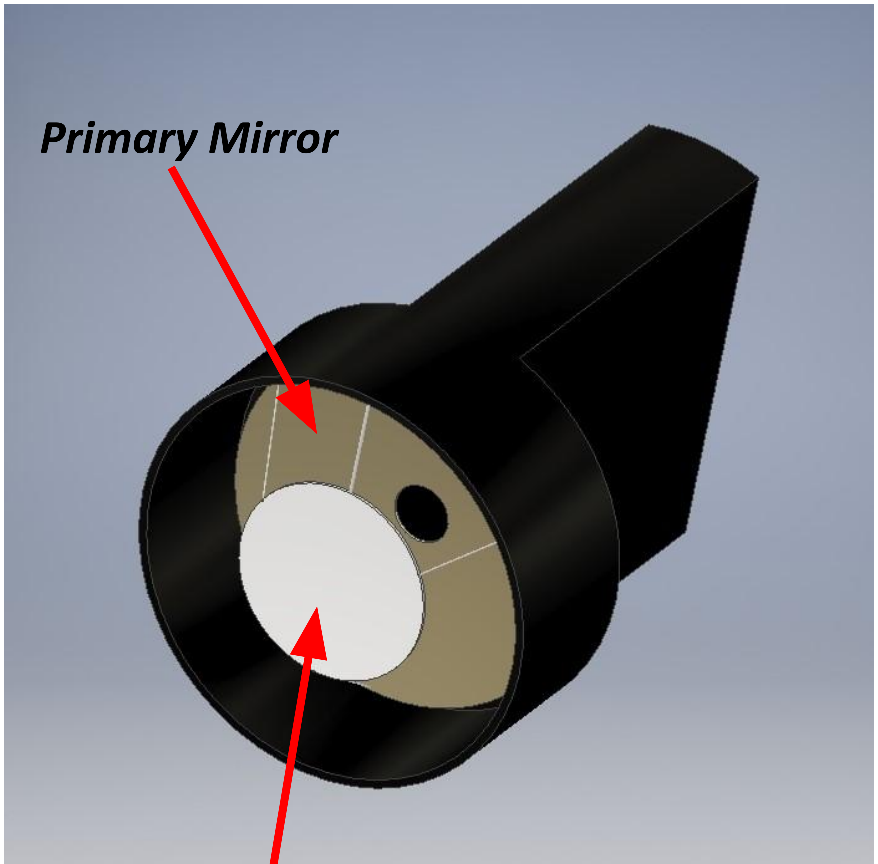
Imaging Constellation

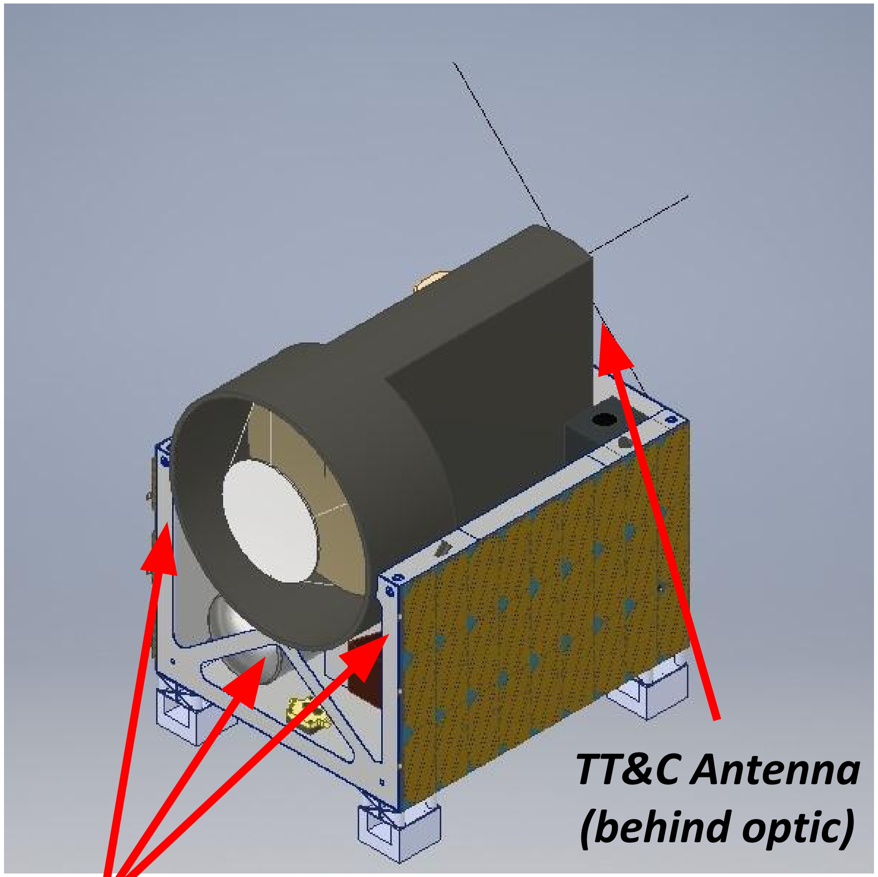
Power Cycle (Operations timeline)



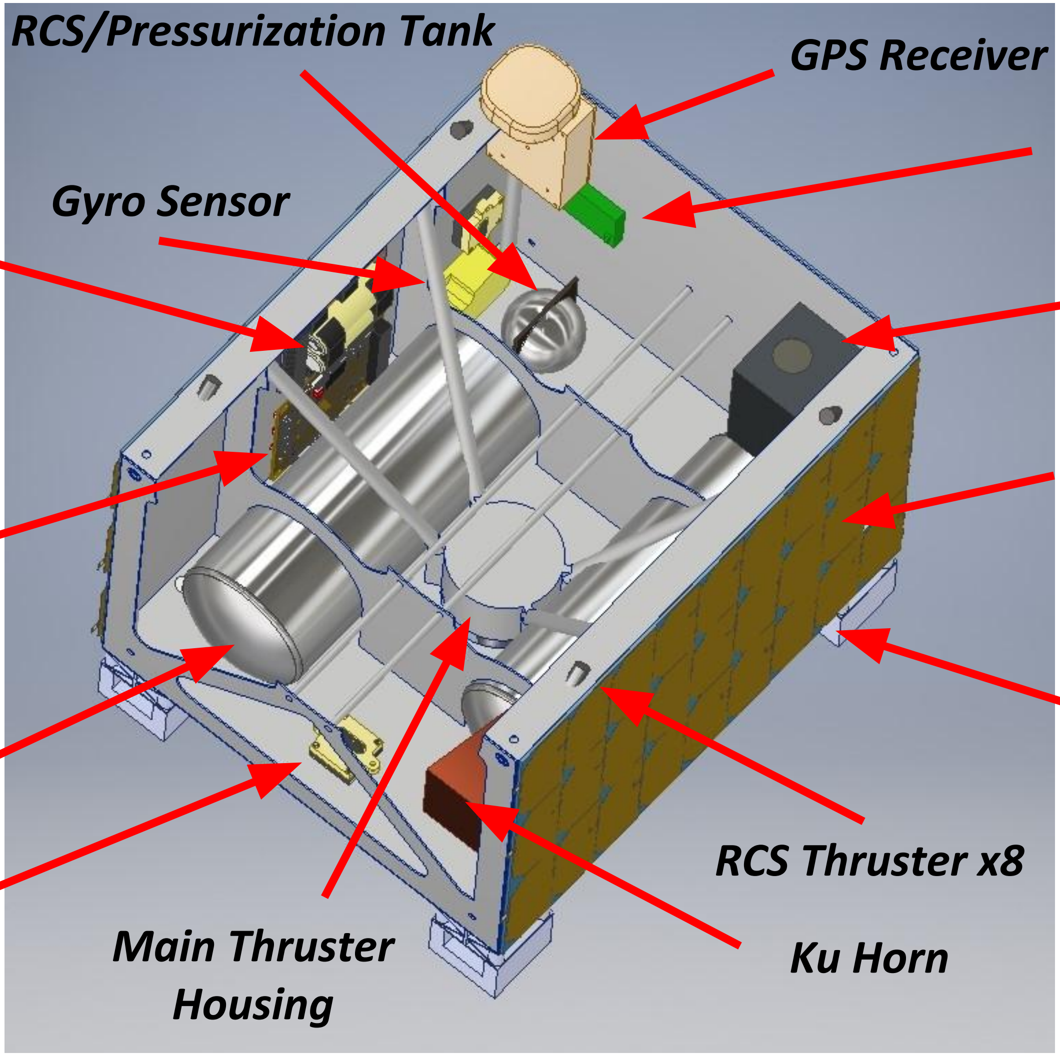
Imaging Constellation

Configuration - Optic Payload





Configuration - Subsystem Components



Imaging Constellation

Moving Forward

- Optics
  - Further develop payload design
  - Consider different telescopes for the different bands
- Specific wavelengths for bands of interest
- Focal plane assembly configuration
- Satellite Configuration
  - Thermal and Structural Analysis
- Redundancy and Failure Mitigation
- Cost analysis

Communications Constellation

Presenter:
Yojar Paz

Communications Constellation

Customer Requirements

- The system shall provide repeater capability for 240 minutes/day
- The maximum time without repeater access is 120 minutes
- The system shall provide beyond line-of-sight communications capability to first responders
- The minimum communications window is 3 minutes

Communications Constellation

Major Trades

Trade	Status	Baseline
Orbit Altitude	Closed	625 km
Variable vs. Invariable Orbits	Closed	Variable
Antenna Type	Closed	4 monopole whips in phase quadrature

Communications Constellation

Orbital Scheme

- LEO altitude trade based on gain, ΔV to launch/deorbit, number of planes and satellites

Constellation Parameters and Allowable Errors

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

Constellation Scheme vs Coverage Latitude

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

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

Sats/Planes Code

Communications Constellation

Phasing Scheme

- Transfer orbit details

Perigee Altitude	Apogee Altitude	Eccentricity	Period
625 km	918 km	0.0205	1.68 hours

- Phasing takes 16.8 hours
  - 3 orbits to phase each satellite with initial orbit to ensure perigee
- 90 m/s Δv required for phasing (to circularize)

Communications Constellation

Propulsion System

- Same thruster as Imaging Satellite
- Responsible for phasing insertion and deorbit burns
- Deorbit drops perigee to 450 km

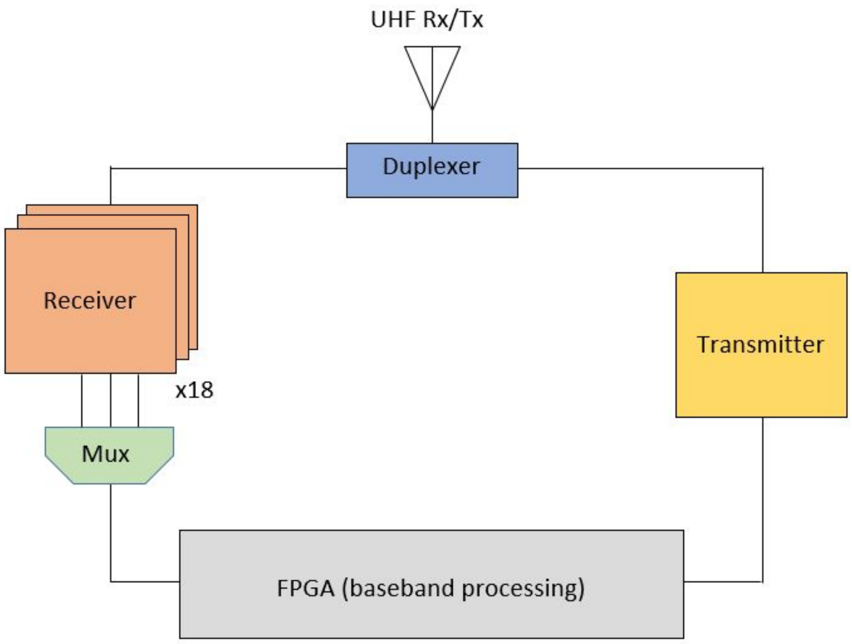
Maneuver	Delta-V (m/s)
Phasing	90
Deorbit	68
Total	**158**

Payload Design

- First responders using tactical UHF radios
  - Based on Harris XL-200P
  - UHF capability
- UHF repeater
  - 18 Software Defined Radios (SDR)
  - Baseline: Vulcun CSR-SDR-U/U
  - Allows for on-orbit variability of frequency and modulation
    - needed for the worldwide operability

Payload Design

- Under Consideration
  - Designing our own payload radio with 18 receivers, 1 FPGA, and 1 transmitter
  - Due to our large volume of channels this could save space and avoid over-designing



Communications Constellation

Link Budget

Link Budget	Uplink: Ground to Satellite	Downlink: Satellite to Ground
Frequency	454 MHz	
Noise Temp	298 K	
Space Loss	148.8 dB	
Signal to Noise Ratio Required	13 dB	
Data Rate	9600 bps	
Receiver Gain	0 dB	-1 dB
Transmitter Gain	-1dB	0dB
Power (RF)	2.5 W	1.5 W
Margin	3 dB	

- Decisions:
  - No. of channels: 18
  - Based on National Interoperability Plan
  - Omni-directional Antenna
    - 4 monopole whips in phase quadrature

Communications Constellation

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Doppler Shift and Encryption

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

Communications Constellation

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ADCS

- 8 cold gas RCS thrusters
  - Same as imaging satellite
  - Used for accurate phasing/deorbit burns
- Determination Sensor: Sun Sensors

Telemetry, Tracking, and Command

- Use existing payload antenna
  - Separate receiver and transmitter
- Sending/receiving health packets, coverage schedule, etc.
- Utilizing 2 communications ground stations

Communications Constellation

Mass Breakdown

Subsystem	Mass (kg)	Percent of Total
ADCS	0.9	9.0
Propulsion	1.2	12
Structure	1.7	17
Thermal	0.3	3.0
Comms Payload	3.7	36
CD&H	0.5	5.0
TT&C	0.1	1.0
Power	1.8	17
Total	**10.2**	100

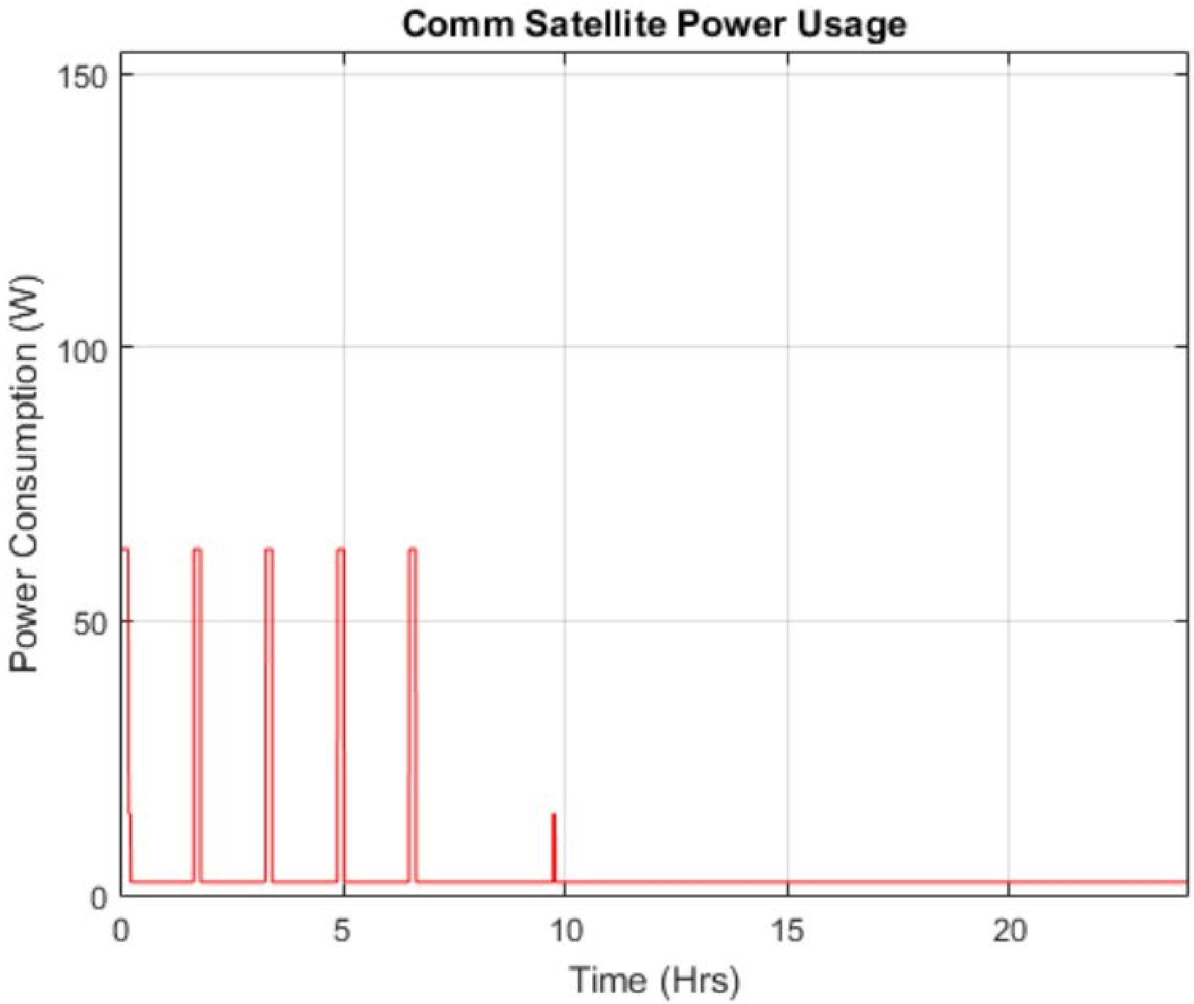
Mass, Power, Thermal

Communications Constellation

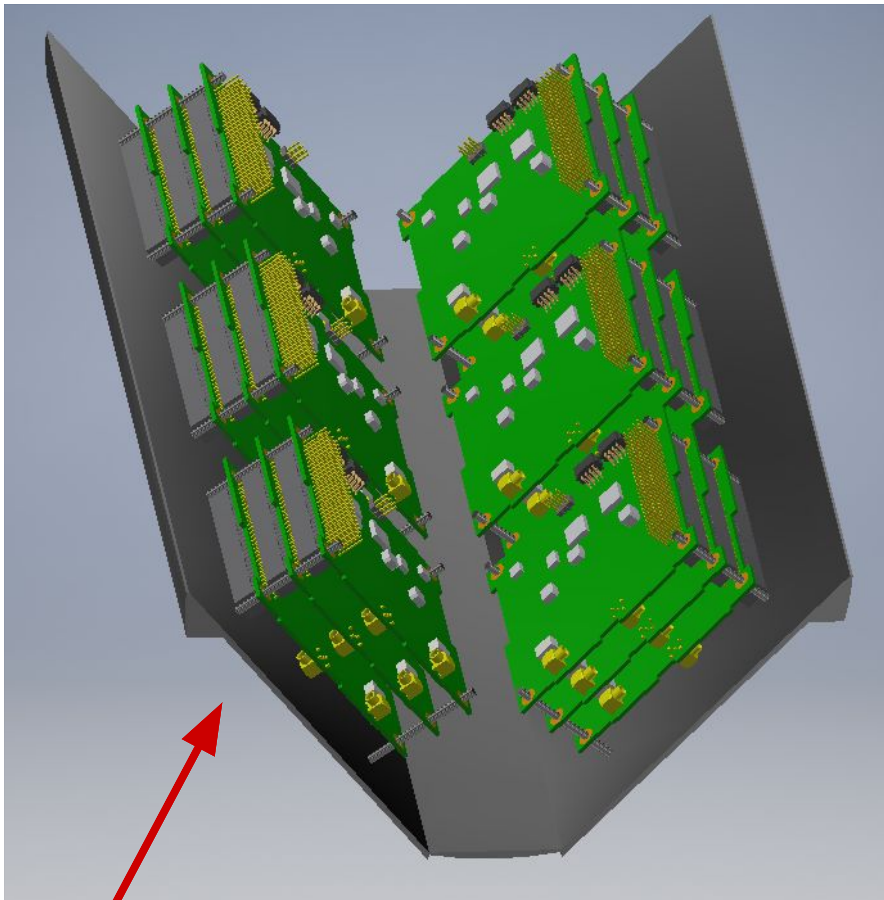
Power

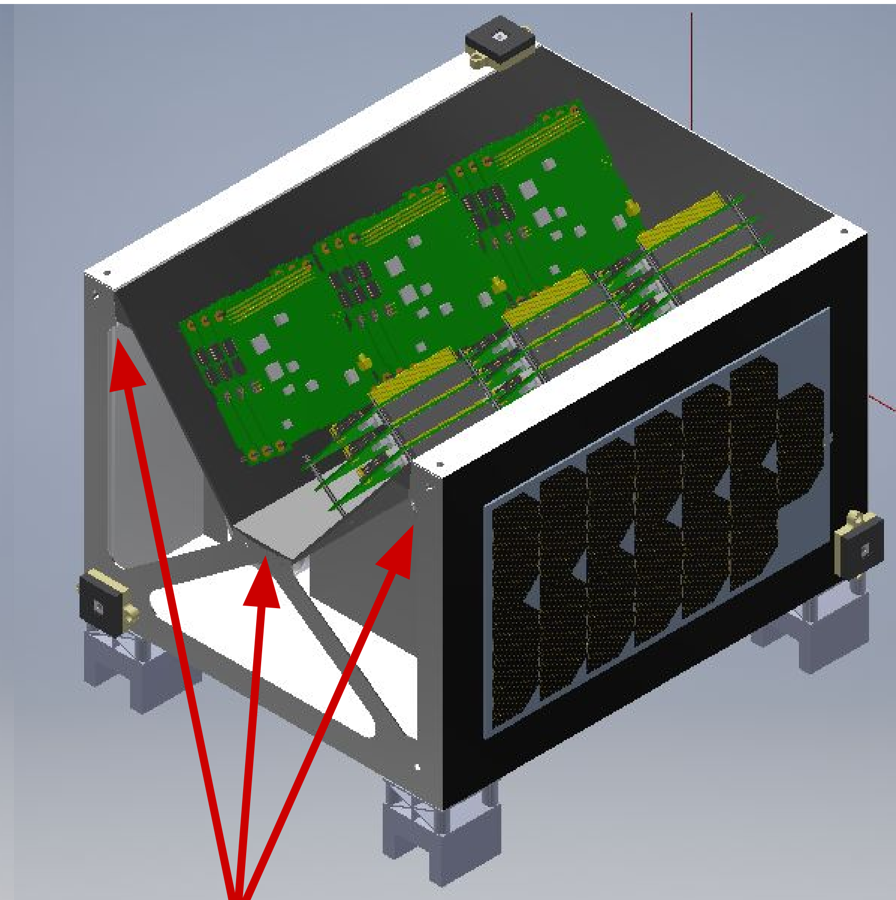
- Standby: 2.3 W
  - In between comms intervals
- Active Payload Power: 63.1 W
  - When above the Area of Interest
- TT&C: 14.8 W
  - During download
- Propulsion Power: 70 W
  - Phasing and Deorbit Maneuvers Only

Power Cycle Graph



Configuration - Communication Payload



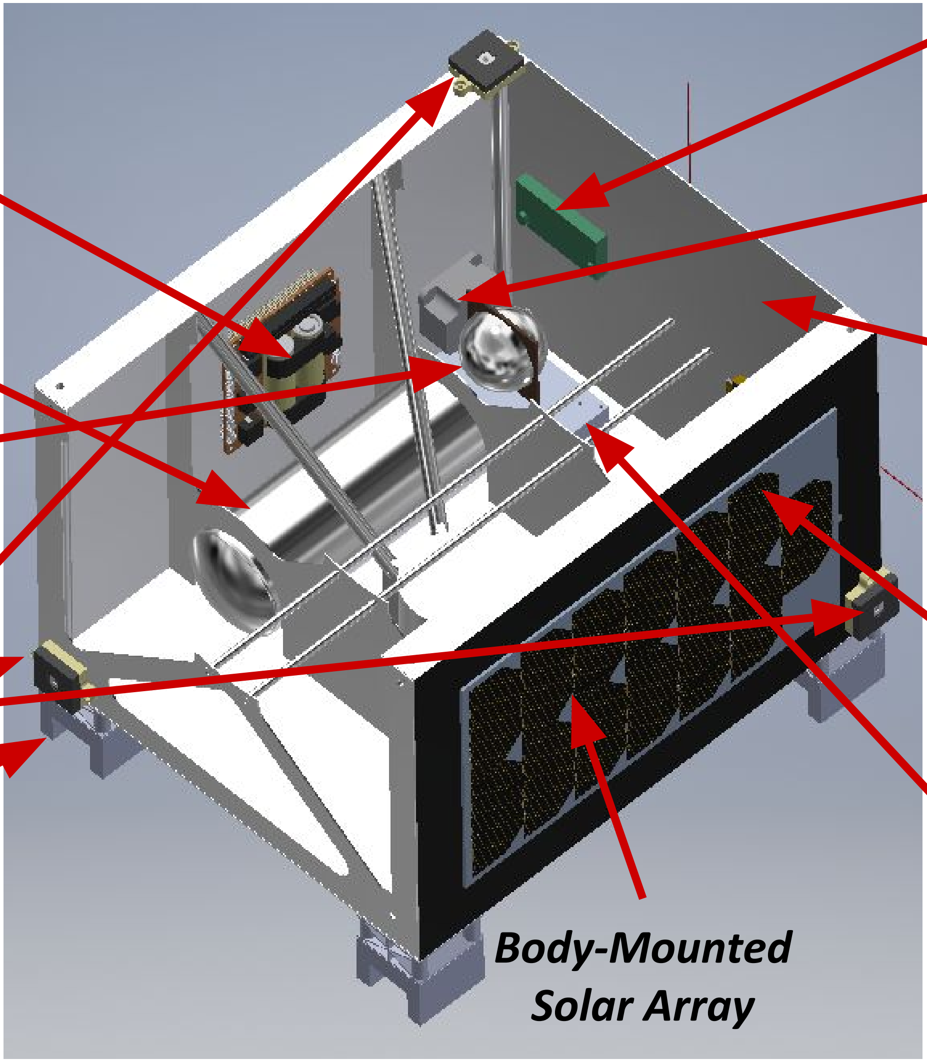


3x6x3 Transceiver V-Configuration (18 Total Channels)

Primary Comms Payload Mounts in the Same Location as Optical Payload

Communications Constellation

Configuration - Subsystem Components



Communications Constellation

Moving Forward

- Thermal Analysis
- Structural Analysis
- Risk/Reliability Study
- Cost Study

Launch

Presenters:

Shane Sheehan

Thomas Rohrbach

Launch

Critical Considerations

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

Launch Derived Requirements

Launch

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Major Trades

Trade	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

Launch Location Considerations

Desirable Latitudes

- Imaging launches:
  - Far from equator, into both ascending and descending nodes of the 97° sun-synch orbit

- Communications launches:
  - Close to equator, into 0-90° inclination
  - Lat-matching not feasible from latitudes higher in value than orbit inclination

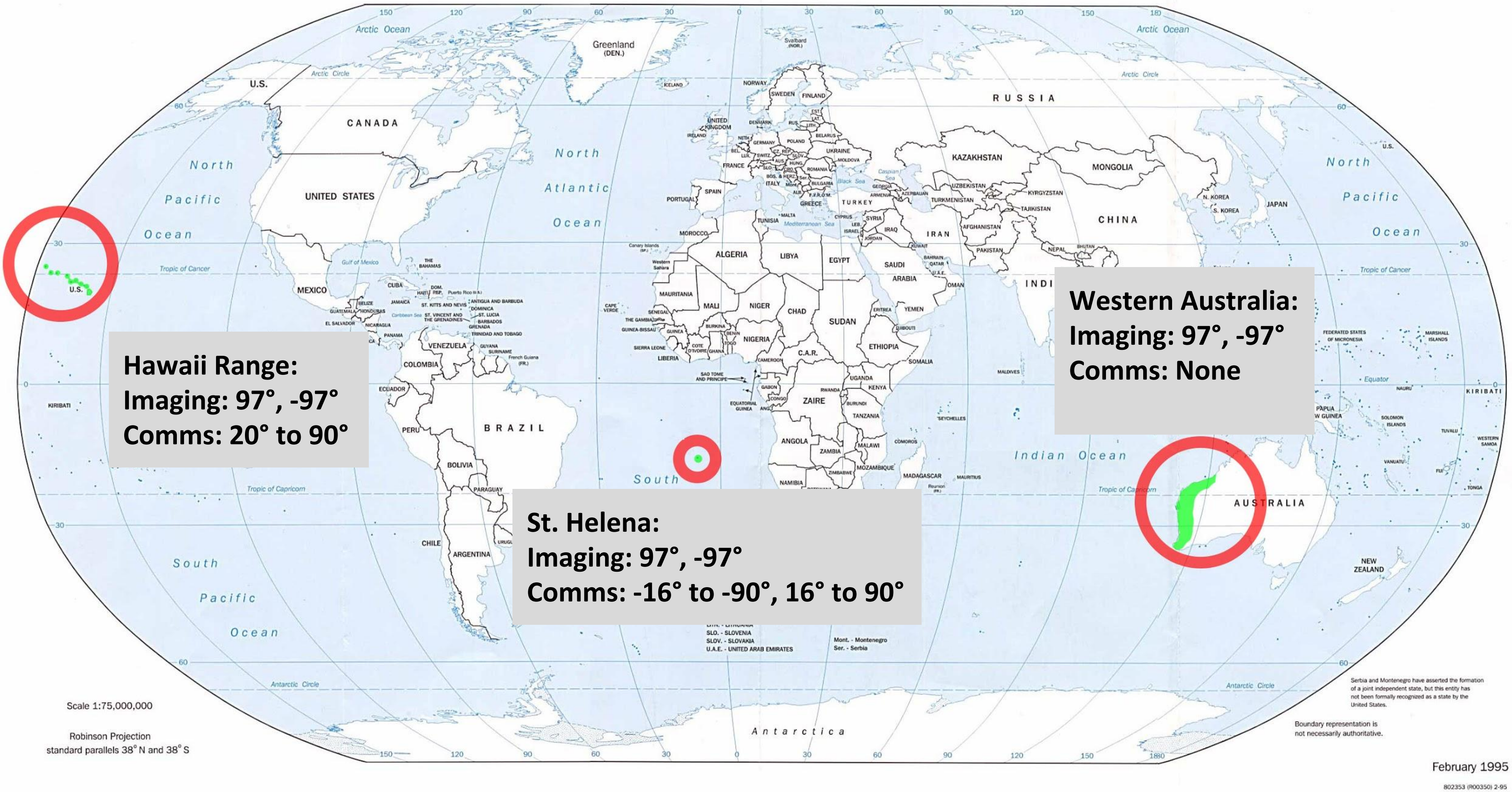
Launch

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
    - Frequency of rain and stormy weather
    - Upper atmosphere wind shear
    - Average and maximum ground wind speeds

Launch Locations: ***3***
Launch Control Sites: ***5***
Launch Pads: ***10***

Ideal Launch Locations for our Architecture



[All Possible Launch Locations]

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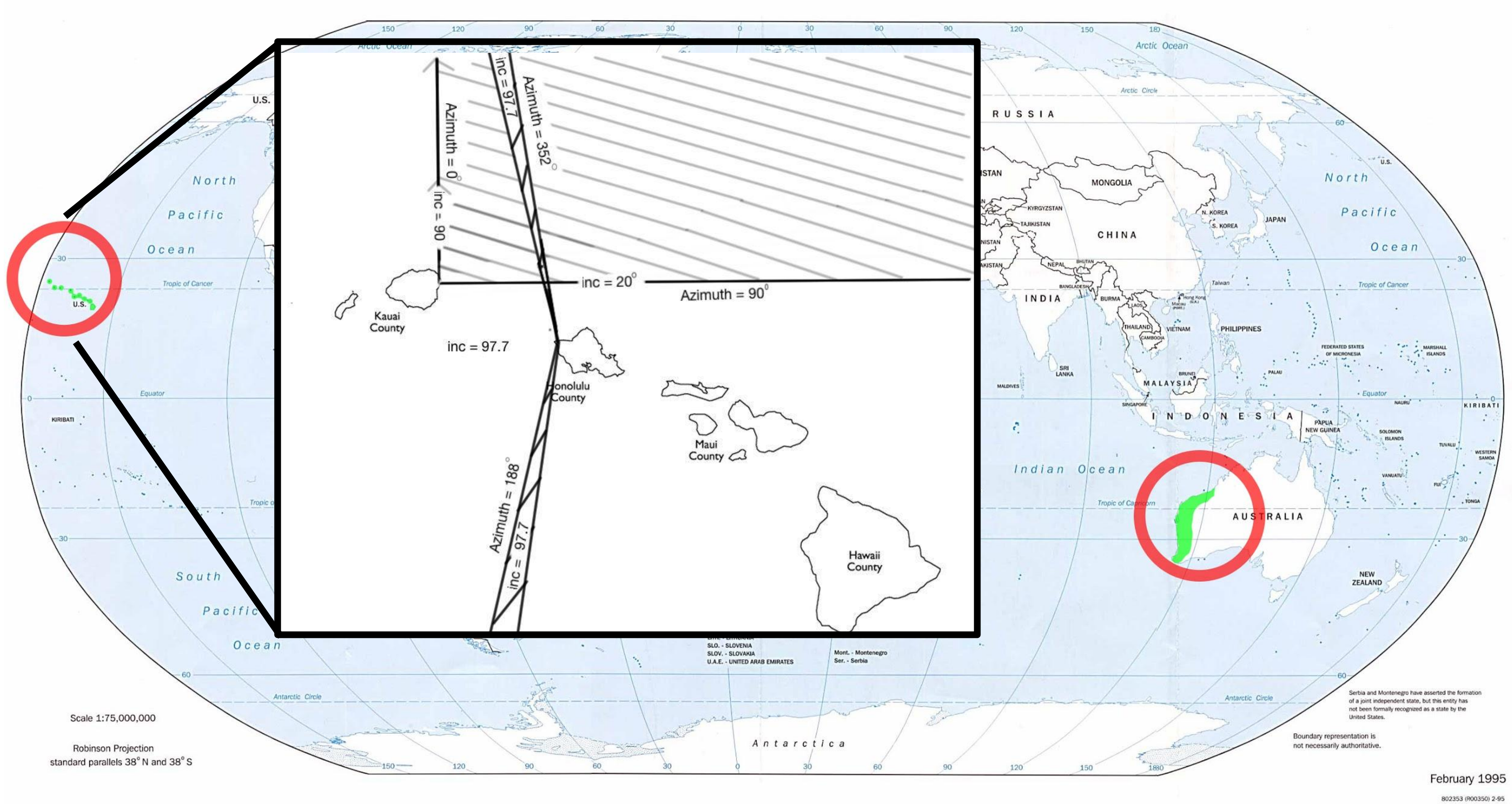
Launch Pad Distribution

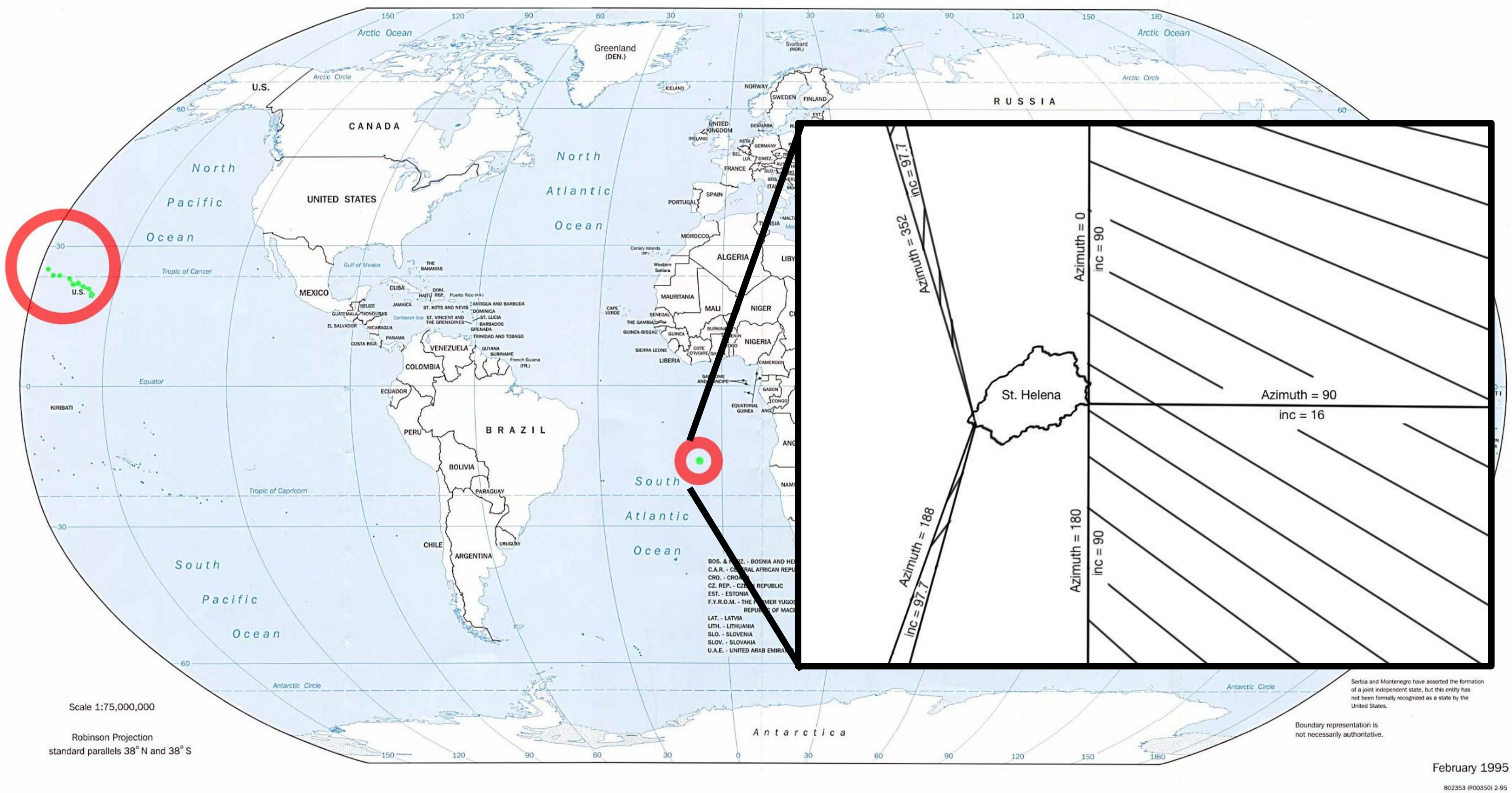
10 total launch pads distributed amongst 5 major launch sites

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

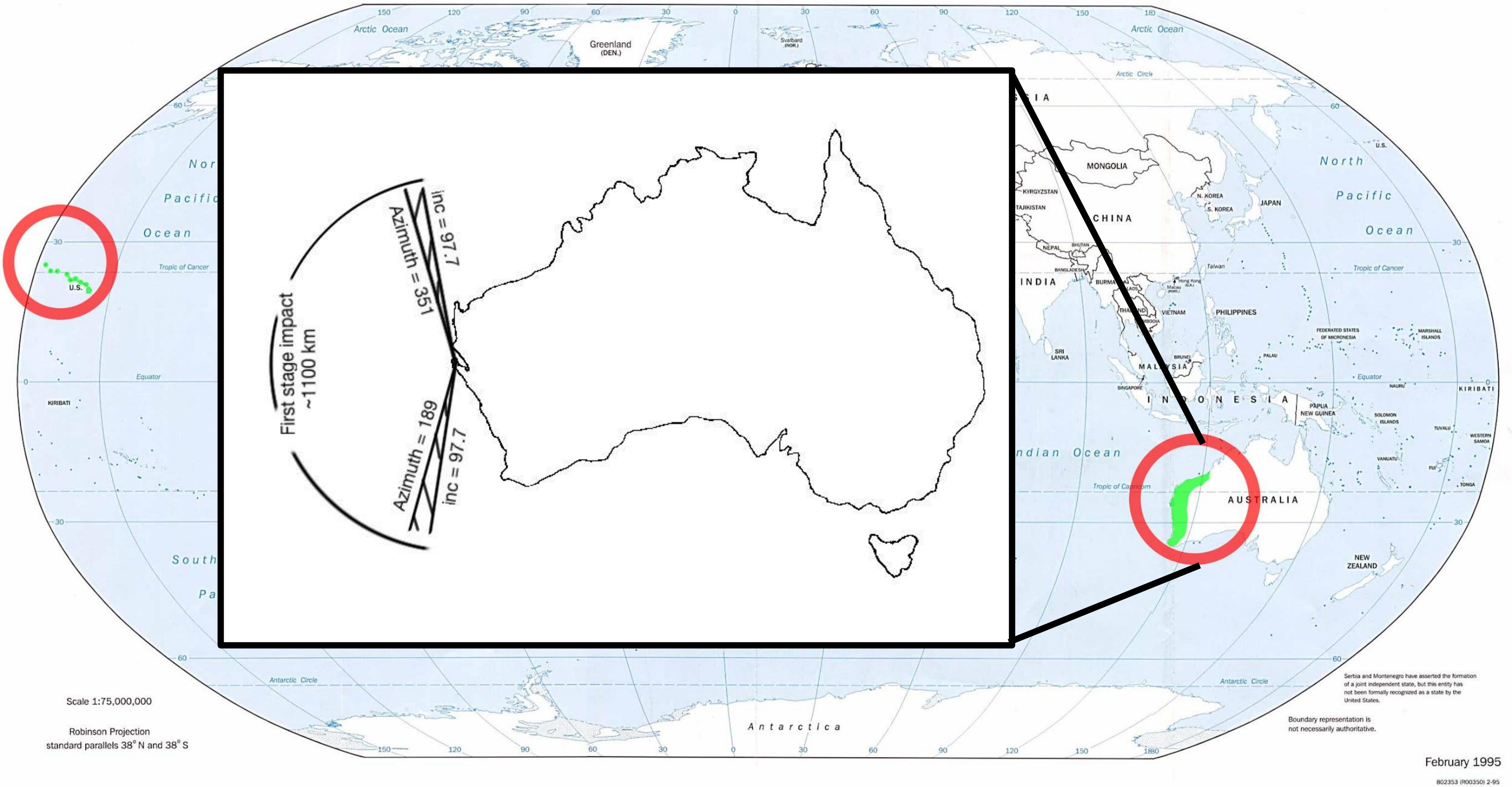
Hawaii Launch Range



St. Helena Launch Range



Australia Launch Range



Launch

Pre Launch

Aiming for expedited launch procedure:

- Payload integration facility at each launch location
  - 100,000 ppm clean requirement
  - Umbilical power ~20 V
  - Temp of 0 to 45 ^{o}C for batteries
  - Temp of -90 to 120 ^{o}C for fuel
  - Humidity level 35 +/- 15%
- Rolling maintenance checks for risk mitigation
- Fully autonomous launch procedure
  - Retracting the hangar
  - Upload trajectories to the avionics system
  - Transfer to internal power and de-energize interface connections

Launch

Derived Requirements from System Architecture

Payload	Imaging	Communications
Satellite Mass	**10.6 kg**	**10.2 kg**
Orbit	Elliptical phasing orbit - 567 X 3167 km	Elliptical phasing orbit - 625 x 918 km
Inclination	90° or 97° ± 0.1°	Latitude ± 0.1°

System Level Launch Vehicle Design Considerations

- Similar payload masses reduce discrepancies between ΔV requirements of launch vehicle
- Design Goal: Ensure all requirements are satisfied by 1 launch vehicle design

Performance Trades

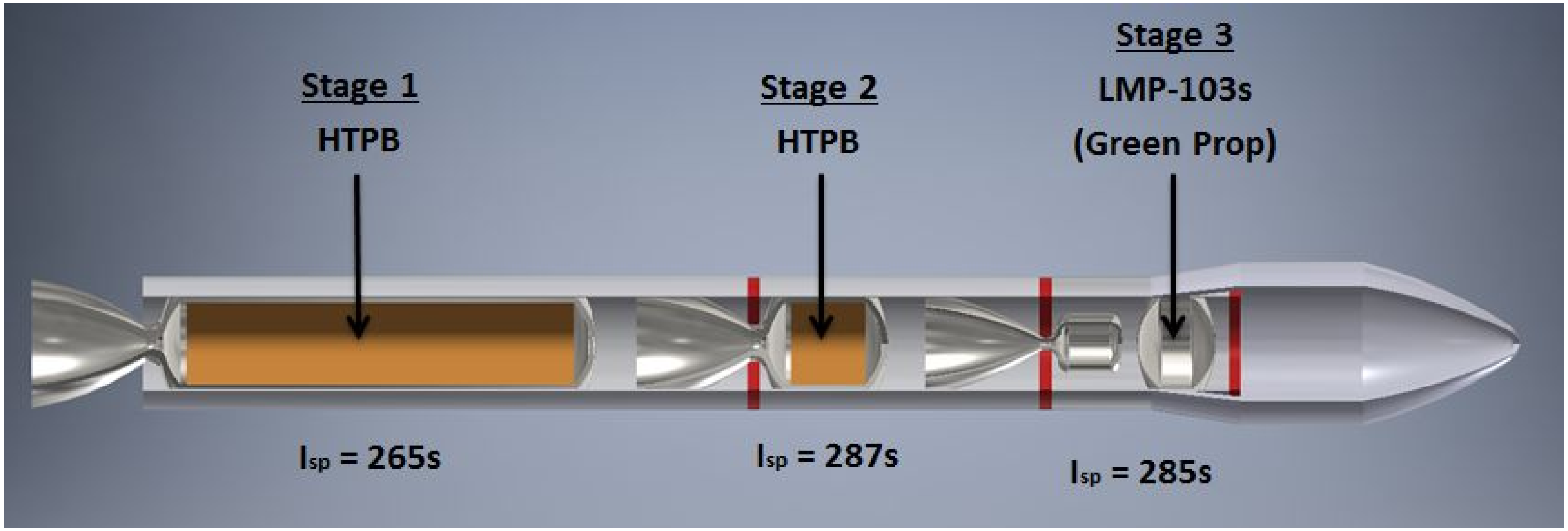
Trade	Status	Outcome
1st and 2nd Stage Propellants	Closed	HTPB 1st and 2nd Stage
3rd Stage: Solid or Liquid Propellants	Open	Liquid Monoprop LMP-103
Thrust Vector Control (TVC) Methods	Closed	Electric Gimbal

Liquid Propellent Study

Propellant Overview

3-Stage Rocket Model

- Rocket Diameter: **1.1 m**
- Fairing Diameter: **1.25 m**
- Height: **13 m**



Liquid Propellent Study

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Mass Breakdown

Component	Mass (kg)
Max Payload	41.2
Fairing	15
Effective Mass	**56.2**
Stage 3 Wet Mass	260
Stage 2 Wet Mass	1100
Stage 1 Wet Mass	5800
Total LV Mass	**7160**

ΔV Breakdown

***Assuming 0.1 mass fraction per stage**

Payload Integration and Deployment

- Goal: Minimize residual ejection velocities and angular rates

Trade	Status	Outcome
Satellite Mounting: Axial vs Radial	Closed	Axial
Payload Release: Pyros vs Actuators	Open	Separation Bolt
Payload Eject: Spring vs Thrusters	Closed	Spring

Payload Configuration

- Axial Configuration
  - Aligned with longitudinal forces
  - Structural mass is less than radial configuration
    - No central mounting structure
- Payload Deployment
  - Short time separation between each payload deployment
  - Desired ejection velocities: 30-50 cm/s
  - Mounting plate mass estimate: 15-20 kg

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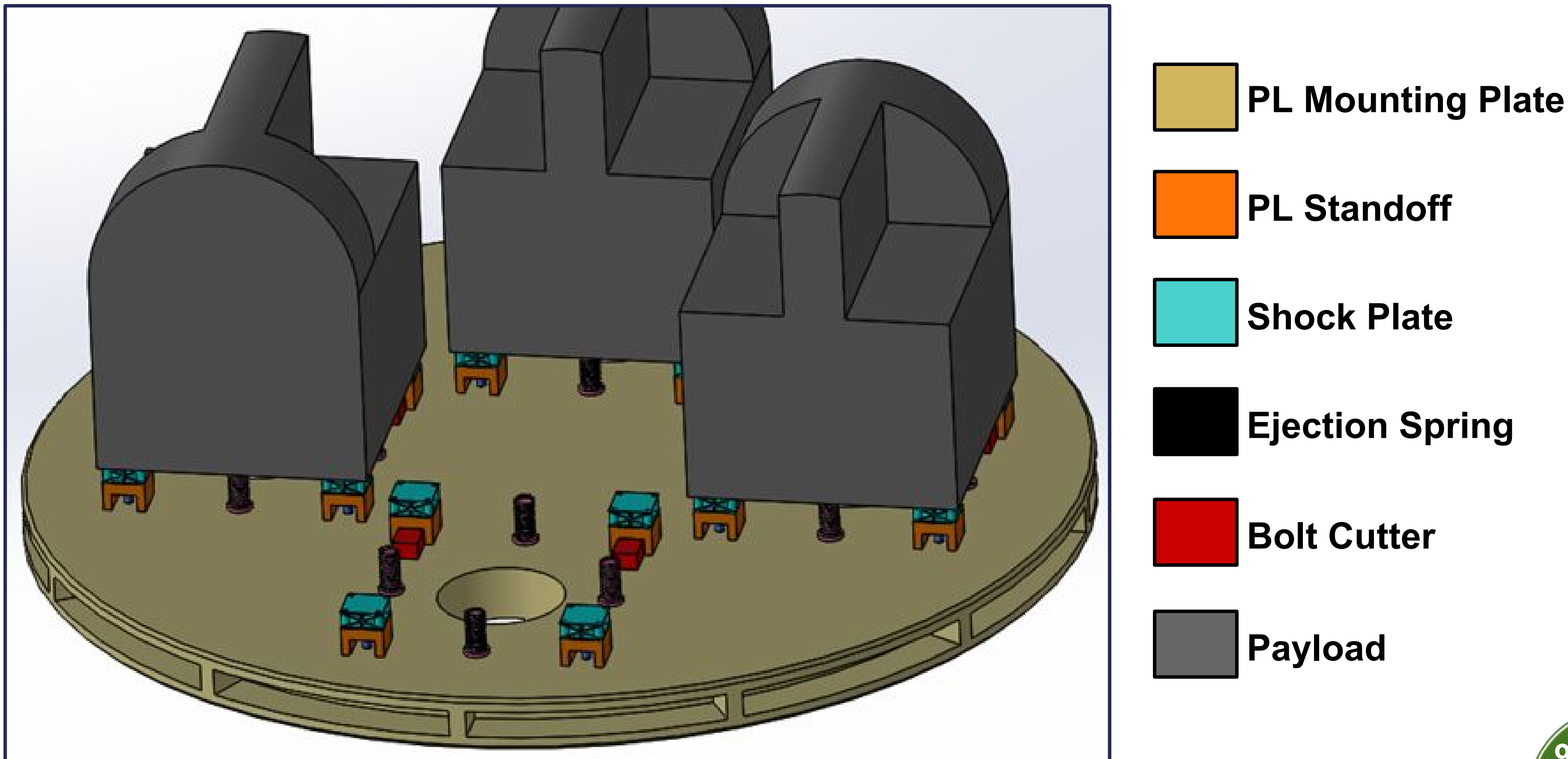
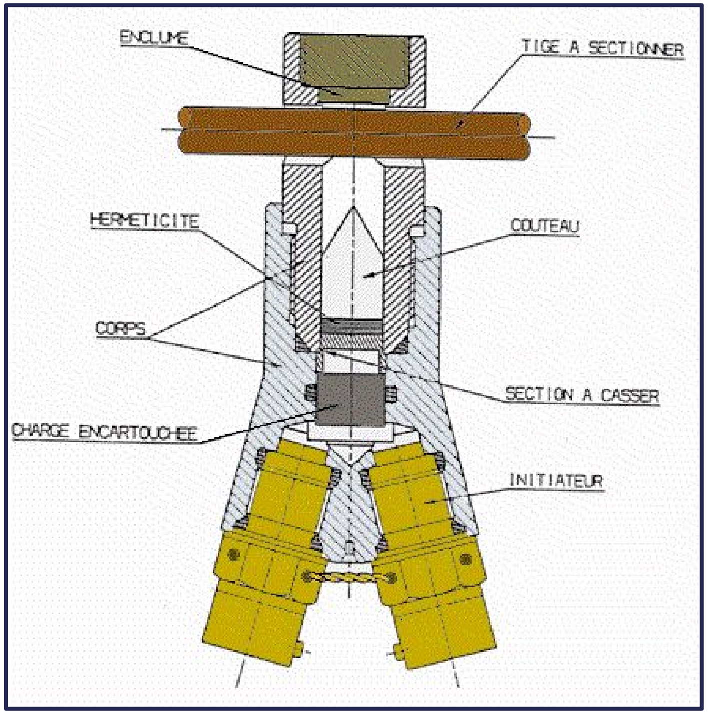
Payload Configuration

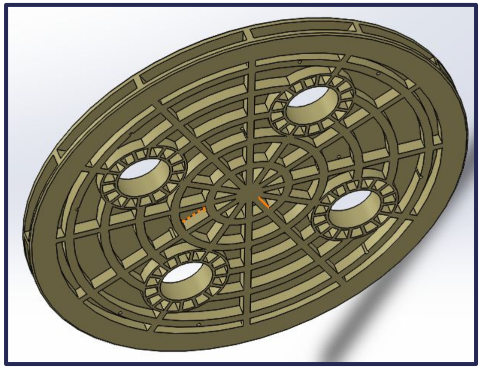
- Payload standoffs and shock plates are permanently fixed on satellites
    - Imaging satellite shown



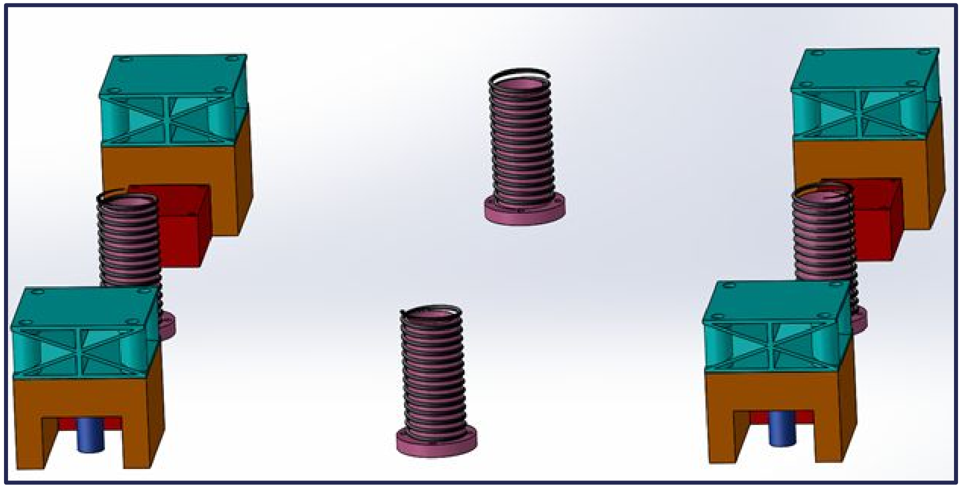
Payload Configuration Components



Bolt Cutter



Payload Mounting Plate



Payload Standoffs and Ejection Springs

Launch

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Telemetry and Tracking

- System uniformity dictates UHF frequency band
  - Patch antenna
- Typical launch failures occur between time of launch to first stage separation
  - Telemetry and tracking communication only applied from launch to first stage cut-off
  - Unreasonable to have downrange ground stations because of orbit variability

Launch

ADCS

- Gimbaled solid rocket booster
  - Yaw and pitch control
- Cold-gas thrusters
  - Roll control
- 1st and 2nd stage open loop control
  - Accelerometers and rate gyros
- 3rd stage closed loop control
  - GPS and INS

TVC Trade

Launch

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Moving Forward

- Application of Loading and Trajectory Program (ASTOS-AeroSpace Trajectory Optimization Software)
- Analysis on 3rd Stage Solid Possibility
- Vibration and Acoustic Analysis
- Thermal Analysis
- Power Budget and Battery Sizing
- Configuration of components
- Fairing design
- Testing and Integration Plan

System Conclusion

Presenter: Ian Hughes-Wickham

System Conclusion

- System wrap up
  - 40 Satellites
    - 24 imaging satellites
    - 16 communications satellites
  - 5 launch sites
  - 10 Launch Vehicles
  - Able to meet all imaging, communications, and timeline requirements
- Path Forward
  - Margin allocation consistency
  - Contingency plans
  - Cost modelling
    - Parametric cost estimation model
  - Standardizing hardware across vehicles
  - Thermal and Structural analysis

Questions/Discussion Session

Support Slides

Major Trades

LEO vs. MEO/GEO

Choice(s) Considered	Pros	Cons	Status
A. LEO	• Quick • Small satellites • De-orbits fast	• High number of planes and sats • Quick pass times	Accepted
B. MEO/GEO	• Reduced number of satellites • Lengthy Pass Times	• Expensive • Large satellites • Response time • Excessive for 6 months	Rejected

Circular vs. Elliptical Orbits

Choice(s) Considered	Pros	Cons	Status
A. Circular	• No orbital maintenance	• Quick passes over target	**Accepted**
B. Elliptical	• Increased time over target	• High altitude apogee • Orbit corrections necessary	**Rejected**

Variable vs. Invariable Orbits

Choice(s) Considered	Pros	Cons	Status
A. Variable	• Reduces number of planes/ launches	• Causes delays	**Accepted**
B. Invariable	• Faster response time • Orbits pre-selected	• Greatly increases number of planes/ sats	**Rejected**

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Separate Communications/Imaging vs. Combined

Choice(s) Considered	Pros	Cons	Status
A. Separate Comms/Imaging	• Less complex satellites • Small components • Different requirements	• More satellites/ planes	**Accepted**
B. Combined Functionality	• Reduced number of satellites	• Large, complex satellites	**Rejected**

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Separate Imaging vs. Combined Imaging Function

Choice(s) Considered	Pros	Cons	Status
A. Separate Imaging Functions	• Decreased complexity per satellite	• More satellites required • Increases cost	**Rejected**
B. Combined Imaging Functions	• Fewer satellites • Reduced cost/ No. of launches	• Complex thermal subsystem • Adds size/ mass	**Accepted**

Correcting Orbits Vs. Non-Correcting Orbits - COMMS

Choice(s) Considered	Pros	Cons	Status
A. Correcting Orbits	• Longer pass times towards EOL	• Addition of on board propulsion	**Rejected**
B. Non-Correcting Orbits	• No need for on board propulsion	• Lower pass times towards EOL	**Accepted**

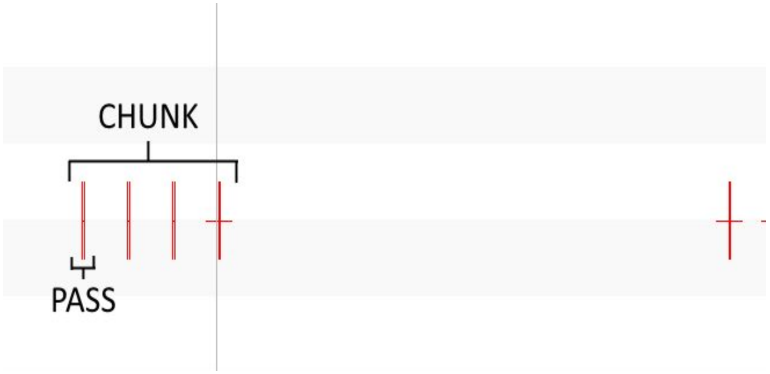
Correcting Orbits Vs. Non-Correcting Orbits - IMAGING

Choice(s) Considered	Pros	Cons	Status
C. Correcting Orbits	• Maintain daily ground track	• More mass for propulsion system	**Accepted**
D. Non-Correcting Orbits for	• No need for on board propulsion	• Drag decrease altitude • J2 affects ground track	**Rejected**

Vehicle Specifics

Comms Orbit Determination Code

- The 500x500 km and all COE combinations defined
- Pass = all target area in view (with elevation angle)
- Passes below 3 minutes removed, “chunk” defined
- Check if time between passes in chunk is <120 minutes
  - Satellites added (equal spacing in true anomaly), repeat



- 24 hours/chunk length for continuous daily coverage
  - Planes spaced out equally in RAAN
- Check if total pass time for all sats, all planes <240 minutes
  - Satellites added, repeat

Comms Satellite Altitude Trade

Alt.	800	775	750	725	700	675	650	625	600	575	550	525
Max # Planes	4	4	4	7	5	5	5	5	5	8	8	8
Max # Sats	10	11	12	16	14	14	15	15	16	22	23	25
Gain: (300 MHz)	5.3	5.1	4.8	4.6	4.3	4.1	3.8	3.5	3.2	2.9	2.6	2.2
Area-to-mass	0.43	0.33	0.25	0.18	0.13	0.1	0.07	0.05	0.04	0.03	0.02	0.01
Deorbiting dV (km/s)	0.217	0.204	0.191	0.178	0.164	0.151	0.138	0.124	0.111	0.097	0.084	0.070

Antenna Trade

Antenna	Beamwidth (deg)	Size	Deployment Necessity	Notes
Helix	120.5	3.98E-10 m^3 (Volume)	Yes	
MMA	150		No	Operates in 2-3 GHz.
Patch		10.2 cm	No	Operates in 2-3 GHz
Dipole	90	Small	Yes	
Monopole	90	.25 m (length)	Yes?	Up to 1.5 dB
Omni	360	Small	No	Avg. 0 dB can be -1 dB
Turnstile	180	~18 cm	Yes	Similar to Omni

Comms Mass-Power-Thermal

Subsystem	Components	Model (hyperlink)	Details	Mass (kg)	Price ($)	Size (cm)	Thermal Output (W)	Power (W)	Temp Range (K)
ADCS	ACS Thrusters		Hybrid ADN DeltaV 1mN Thruster	0.297					263 to 333
	Attitude Sensors		Star Tracker	0.35	75000	7.9 x 5.9 x 4.6	0.75	1	233 to 353
	Rate Gyroscope	Physical Component	(x1 - 3 axis)	0.055	800?	3.9 x 4.5 x 2.2		1.5	233 to 358
	Position Sensor		GPS Receiver	0.16	7000	4.6 x 7.1 x 1.1		<1	263 to 323
	Pos Sensor Antenna		GPS Antenna	0.082					
Propulsion	Engine		5N HPGP Thruster	0.36		5x21.6	7.2	8	
	Phasing Propellant		90 m/s (3.81)	0.187					268 to 323
	Deorbiting Propellant		68 m/s	0.138					268 to 323
	Pre-Burn Orientation Propellant		very small ---->						268 to 323
	Tank and Valves		Not accurate --->	0.5		2661.3cm^3			244 to 344
Structure	Frame/ Harnessing		(~20% of total mass)	1.6854					78 to 336
Thermal	Heater	There's a few, see notes		0.2			12	12	
	Cooling	Bellows, dim in notes		0.1		0	0	0	
Comms	Antenna		Patch w/ Quad Whips	0.1				50.3	
	Transceiver (x18)			3.6		10 x 10 x 2	0.0277	0.277	218 to 398
TT&C	Astrodev Transciever			0.052		6.5 x 3.3 x 1			253 to 343
CD&H	Computer	SpaceMicro CSP		0.446	7500	10 x 10 x 0.6		1	273 to 343
Power Units	Batteries	2 of these --->	Gom Space: (Lithium-Ion), 70 Whr, 14.8 V, 1P-4S	0.6	10000	10 x 10 x 6 cm	0.3		273 to 318
	Solar Panels		(Cells + Structure), 425 cm^2, w/ packing factor 500 cm^2	1.2	5000	Each (x5): 10 x 10 x 0.3	2.4		235 to 398
	TOTALS		Total W/O Frame (kg)	8.427	104500				
			Total W/ Frame (kg)	10.1124					
	RATING			Ok			Not Sure	Ok	
	Good			< 35				< 45	
	Ok			35-40				45-55	
	Bad			40 <				55<	

Return

Propulsion Method Decision

Possible Engines

												Scenario 1 (Phase, Station Keeping, & Deorbit)			Scenario 2 (Station Keeping & Deorbit)	
Type of thruster	Make / Model	Propellant Type	Engine Mass (kg)	Thrust (N)	Exhaust Velocity (m/s)	ISP (s)	Power Required (W)	Weight Flow Rate (wdot = N/s)	Mass Flow Rate (kg/s)	Assumed Spacecraft Dry Mass w/o sail (kg)	Assumed Spacecraft Dry Mass with sail (kg)	Total Prop Mass (kg)	Burn Time: Phase (sec)	Burn Time: De-Orbit (sec)	Total Prop Mass (kg)	Burn Time (sec)
Green Monoprop Thruster	HPGP	LMP-103S(Green)	0.38	0.69	2158.2	220	8	0.004	0.0003197	20.68	20.68	0.9106103627	2306.575042	541.7526487	0.7312873916	2287.417553
Electrospray	BET-100	Ionic Liquid	1.15	0.001	7848	800	15	1.25E-06	1.28E-06	21.45	21.45	0.2556978167	161284.4586	38479.46072	0.2059711539	160914.964
PPT	BmP-220	Teflon(PTFE Solid)	0.5	0.00002	5253	536	7.5	0.000765	0.0009323	20.8	20.8	0.3715257897	8111621.046	1929616.514	0.2991033093	8083873.225
Green Monoprop Thruster	BGT-X5	AF-M315E(Green)	1.5	0.5	2185	223	20	0.000224	0.000228	21.8	21.8	0.947901488	3366.542236	790.9204312	0.7612743592	3338.922628
Green Monoprop Thruster	MPS-130	AF-M315E(Green)	2.2	6	2354.4	240	7	0.00625	0.000637	9.14		3.94	5416.7	144.5	0.48	144.5
Green Monoprop Thruster	HPGP	LMP-103S(Green)	0.75	22	2501.55	255	TBD	0.0087945	0.008794	9.14		3.5	348.3	9.38	0.433	9.38
Green Monoprop Thruster	BGT-5	AF-M315E(Green)	3.5	5	2254	230	50	0.00221	0.002218	23.8	23.8	1.002527491	365.9623334	86.03383015	0.8052481574	363.0514686

Return - Phasing Prop

Communications Constellation

Components

- Comms Payload: 18 solid state UHF radios
- Antennas: 4 whips in phase quadrature
- Propulsion:
  - Phasing: SSC 5N Thruster
  - ADCS: MOOG SVT01 10 - 50mN
- Determination Sensor: TBD
- Normal Op: Magnetorquers
- CD&H: Cubesat Space Processor
- Solar Arrays: Body-mounted GaAr cells
- Batteries: Li-ion
- TT&C: UHF Transceiver
- GPS: TBD
- PDU: TBD

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

Back

Imaging Mass-Power-Thermal

Subsystem	Components	Model (hyperlink)	Details	Mass (kg)	Price ($)	Size (cm)	Thermal Output (W)	Power (W)	Temp Range (K)
GNC	Star Tracker	Standard NST	(Star Tracker)	0.35	75,000	10 x 5.5 x 5	0.75	1.5	233 to 353
	Sun Sensor	SSOC-A60	x3 (2 axes determination)	0.025	7,200	3 x 3 x 1.2		< 0.036	233 to 358
	Rate Gyro/Accelerometer	OEM-STIM-300	(x1 - 3 axis)	0.055	8,600	3.9 x 4.5 x 2.2		1.5	233 to 348
	Magnetometer	HMC2003	x1 - 3 axis	0.1		2.73 x 1.2 x 1.97		20 mA	
	Position Sensor	OEM-615	(GPS)	0.16		4.6 x 7.1 x 1.1		<1	233 to 358
	Position Sensor Antenna	ANT-GPS	(GPS Antenna)	0.082					
	RCS Thruster	Hybrid ADN Delta-V / RCS System	Total Fuel Mass	0.1347					
Propulsion	Engine	SEE BELOW	5 N HPGP	0.36	25,000	17cm (Long, Valves can be modified)	7.2	8	
	Phasing Propellant	LMP-103s	575 m/s	1.68	2,016				268 to 323
	Deorbiting Propellant	LMP-103s	18 m/s	0.0451	54.12				268 to 323
	Orbital Maintance Propellant	LMP-103s	75 m/s	0.192	230.4				268 to 323
	Tank and Valves		Etc.	TBD		2661.3cm^3			244 to 344
Structure	Frame/ Harnessing		(~20% of total mass)	1.44854		28x27x42			78 to 336
Thermal	Heater	There's a few, see notes		0			12	12	
	Cooling	Bellows, dim in notes		0.1		0	0	0	
Imaging Payload	Optics			3		25(diam), 35(length)	0	0	263 to 323
	Focal Plane Assembly		Sensor	0		24.23 x 5	66	132	263 to 323
Comms	Antenna	http://www.ainfoinc.com/en/pro_pdf/ne		0.15		Horn, 4.3x5.2x11.2 cm, Phase-Quad UHF, ~20.5x20.5x0.5 cm	0	0	233 to 353
	Amplifier	http://www.rflambda.com/pdf/lownoise	Image Data DL	0.03		1.5x3.5x2 cm	30	50	233 to 358
TT&C	Radio	http://www.astrodev.com/public_html/		0.05		6.2x3.3x1.1 cm	0.25	0.25	238 to 358
	Computer	http://www.spacemicro.com/assets/da		0.446		9.0x9.6x11.8 (PC-104)	0.15	1.5	218 to 398
Power Units	Batteries x 2	https://gomspace.com/Shop/subsyste	(Lithium-Ion)	0.4		8.93 x 9.29 x 2.56 cm	0.3		233 to 358
	Solar Panels x3		(Cells + Structure)	1.8		27 cm x 27 cm on three faces	2.4		173 to 398
	TOTALS		Dry Mass:	8.69124			AVG. THERMAL	AVG. POWER:	
			W/ Phase Wet Mass:	10.60834			8.03385	6.3925	<<< See Day in the lif
			W/O Phase Wet Mass:	8.92834					https://docs.google.co
	RATING			Ok			Not Sure	Ok	
	Good			< 35				< 45	
	Ok			35-40				45-55	
	Bad			40 <				55<	

Return

Sensor Type Trade

	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

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Planes of Auxiliary Images

Metrics Considered:

- Ground track differences
- Image quality
- Redundancy
- Launch vehicle requirements

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ACS Trade

Metrics Considered: Fully Actuated Control System

	Vacco Thrusters (12)	Reaction Wheels (4) and Magnetorquer (1)
Power, Watts	15 (pulse, TBR)	1.5 (max)
Mass, Kg	0.29 (fuel mass)	0.35 (1.4 total)
Jitter	No	Yes

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Reaction Wheels for Imaging

- Aligned 57 degrees off the xy plane of the spacecraft body frame
- Momentum budget: 0.1 Nms
- Dimensions
  - Radius: 3.5 cm
  - Thickness: 2.5 cm
  - Mass: 0.35kg
  - Max Angular Momentum: 0.1 Nms
- Duty cycle

Maneuver Type	Detumble	Image	Downlink	Stationkeep	Account for disturbances
Accumulated Momentum (Nms)	0.038	0.002	0.012	0.002	0.015/day

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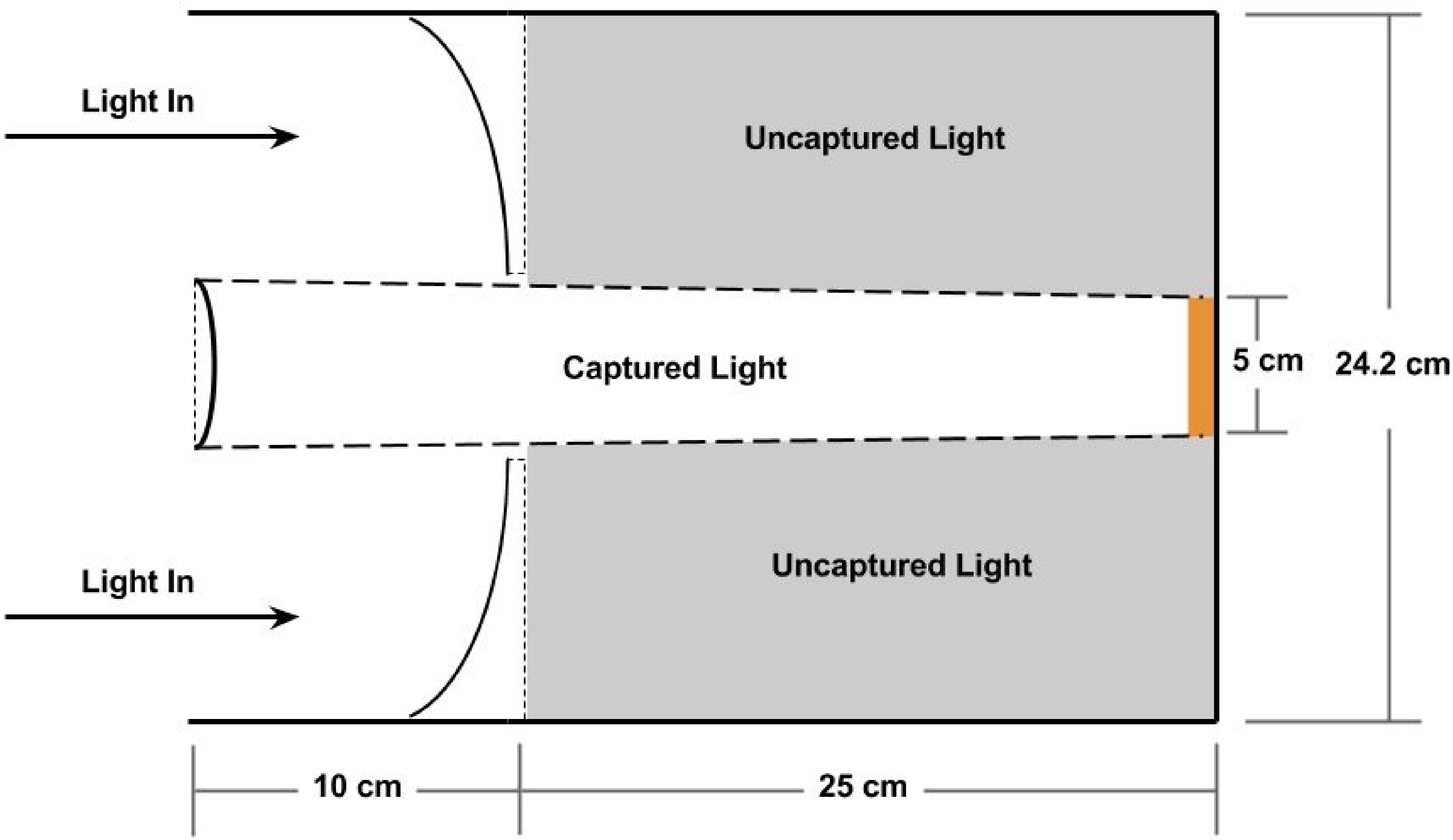
Optics Light Capture - Secondary View



Return to Imaging Constellation - Optical Payload

Power Subsystem

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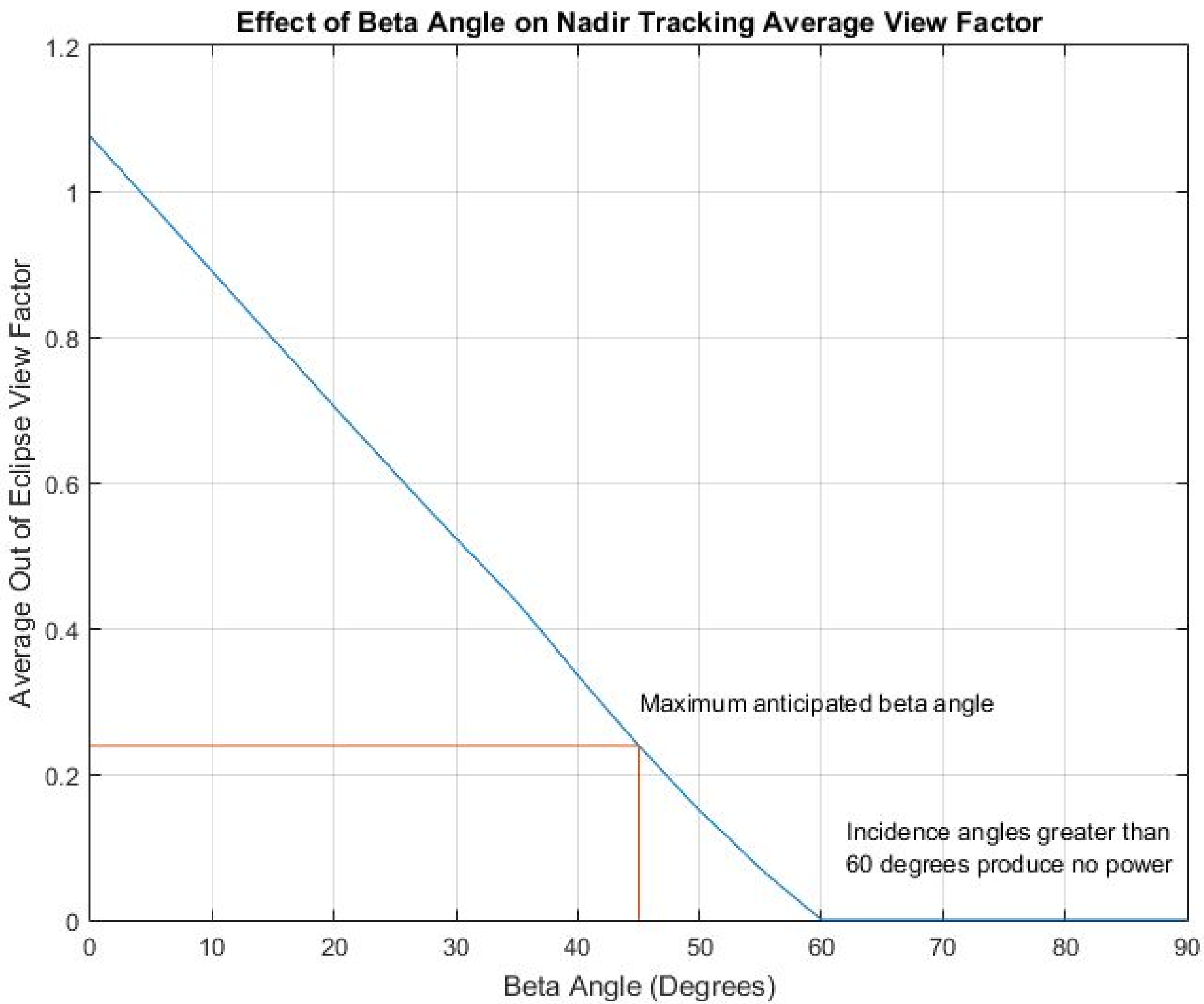
Baseline Assumptions for Battery/Solar Panel Sizing

	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

Power Subsystem



Operations Timeline

Operation Temperatures

Imaging Satellite

Component	Temperature Range (°C)
Attitude Sensor	-40 to 80
Rate Gyroscope	-40 to 75
Position Sensor	-40 to 85
Phasing Propellant	-5 to 50
ADC Propellant	0 to 50
Tank/Valves for Propellant	-29 to 71
Structure Frame	-195 to 93
Optics	0 to 65
Comms Equipment	-40 to 80
CD&H Amplifiers	-40 to 80
CD&H Computer	-55 to 125
Batteries	-40 to 85
Solar Panels	-100 to 125

Return to Thermal Considerations

Ground Station Type

Metric	MOBILE	FIXED	WEIGHT	Mobile Total	Fixed total	JUSTIFICATION
Before Delivery:						
Minimize staffing	7	4	0.3	2.1	1.2	lower cost
Storage:						
Ease of storability	8	5	0.3	2.4	1.5	less space
Minimizes maintenance	6	4	0.6	3.6	2.4	building needs more maintenance than truck/suitcase
Disaster Occurs - 24 hours:						
Eases transportation	3	10	0.6	1.8	6	fixed does not need transportation
Minimizes transportation time	3	10	0.8	2.4	8	
Minimizes setup/deployment deployment time	8	9	0.8	6.4	7.2	
Capable of sending signal	5	5	1	5	5	
Minimize preparation time	8	9	0.8	6.4	7.2	
Mission - 6 months:						
Minimizes maintenance	8	7	0.7	5.6	4.9	
Minimizes staff	5	8	0.5	2.5	2.5	
Minimizes time to sending signal to sats	8	4	0.8	6.4	3.2	ability to send 15% cmd
Capable of sending signal	0	0	1	0	0	
End of Mission:						
Ease of disposability	0	0	0.2	0	0	
Totals				**44.6**	**49.1**	

LV Baseline

*What our **Closed** Trades Determined*

- Build our own launch vehicles
- Build our own launch sites
- Land launch

*What our **Open** Trades Determined... So far*

- Separate launch vehicle configurations for imaging and comms satellites
- HTPB as solid fuel option
- MMH/N2O4 as liquid fuel option

Launch Vehicle: Build vs. Buy

Decision: Build

- 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 Site: Build vs. Use Pre-existing

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

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**	

**Not possible if high altitude is required*

Back: Pre-Launch Trades

Solid Propellant Trade

Fuel:	Isp (sec)	Density (kg/m^3)	Storability:	Cost/Availability:	Toxicity Level:	Value:
Weights:	0.7	0.7	1	0.7	0.8	
HTPB	260	1854.553615	Good 5+ years	~16 $ / kg	Moderate	18.2
	4	5	6	5	3	
DB	220	1605.434473	NG leaks	Moderate	Bad	10.6
	3	3	2	4	2	
PBAN	260	1771.513901	Good 10+ years	~6 $ / kg	Moderate	18.2
	4	4	6	6	3	
CTPB	260	1771.513901	Good 10+ years	~70 $ / kg	Moderate	16.8
	4	4	6	4	3	

- HTPB was selected for baseline tests due to its performance parameters
- PBAN propellant is the most affordable.
- HTPB has slightly better performance metrics for slightly more cost.

Back: Pre-Launch Trades

Liquid Propellant Trade

Fuel/Ox:	**Isp (sec)**	**Density (kg/m^3)**	Storability:	Cost/Availability:	Toxicity Level:	Value:
Weights:	0.7	0.7	1	0.8	0.8	
MMH/N2O4	280	1.80556	Good storage properties	Very expensive	Bad	15.1
	5	6	5	2	1	
UDMH/N2O4	277	1.140794224	Most stable Hydrazine	Very expensive	Moderate	16.3
	5	4	6	2	3	
Hydrazine/H2O2	269	1.219330855	Worse temperature range	Not used on many engines	Bad	12.7
	4	5	4	1	2	
Hydrazine/N2O4	286	1.195804196	Worse temperature range	Very expensive	Bad	14.1
	6	5	4	2	1	

- MMH/N2O4 has the best performance metrics but is the most toxic
- UDMH/N2O4 is the least toxic of the hydrazine family but has lower performance metrics

Back: Pre-Launch Trades

Solid Versus Liquid Trade

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 LMP-103S liquid monopropellant due to the known method of orbital variance, while the solid propellant method is currently unknown

Back: Pre-Launch Trades

Liquid Propellant Study

Fuel	Type	Isp (s)	Density (kg/m3)	Mission Cost (millions of $)	Toxicity
LMP-103s	monoprop	~285	1.227e3	~5.88	Not toxic
Hydrazine	monoprop	~260	1.021e3	~6.04	High
UDMH/NTO	biprop	~333	1.140e3	~4.32	High

- Mission cost calculated for third stage of launch vehicle

Liquid Monopropellant Trade

Fuel	Type	Isp (s)	Density (kg/m3)	Mission Cost ($)	Toxicity
LMP-103s	Monoprop	~285	1.227e3	~192,000	Not toxic
Hydrazine	Monoprop	~260	1.021e3	~201,000	High

- Mission Cost calculated for mass of satellite prop
- Benefits
  - 30% Higher Performance than hydrazine
  - Shipment and handling of fuel(No SCAPE suits required)
  - Reduced risks for other satellites and launch site
  - Cost $1200/kg

Launch Subsystems

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Thrust Vector System Trade

	Cost	Complexity	Performance	
Weighting	0.5	0.6	1	**TOTAL**
Jet Vane	0.5	0.6	0	1.1
LITVC	0.25	0	0.5	0.75
Gimbal	0	0.25	1	1.25
Auxiliary	0	0	1	1

Back to Launch

Launch Ground System Trade

	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 protecive 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.

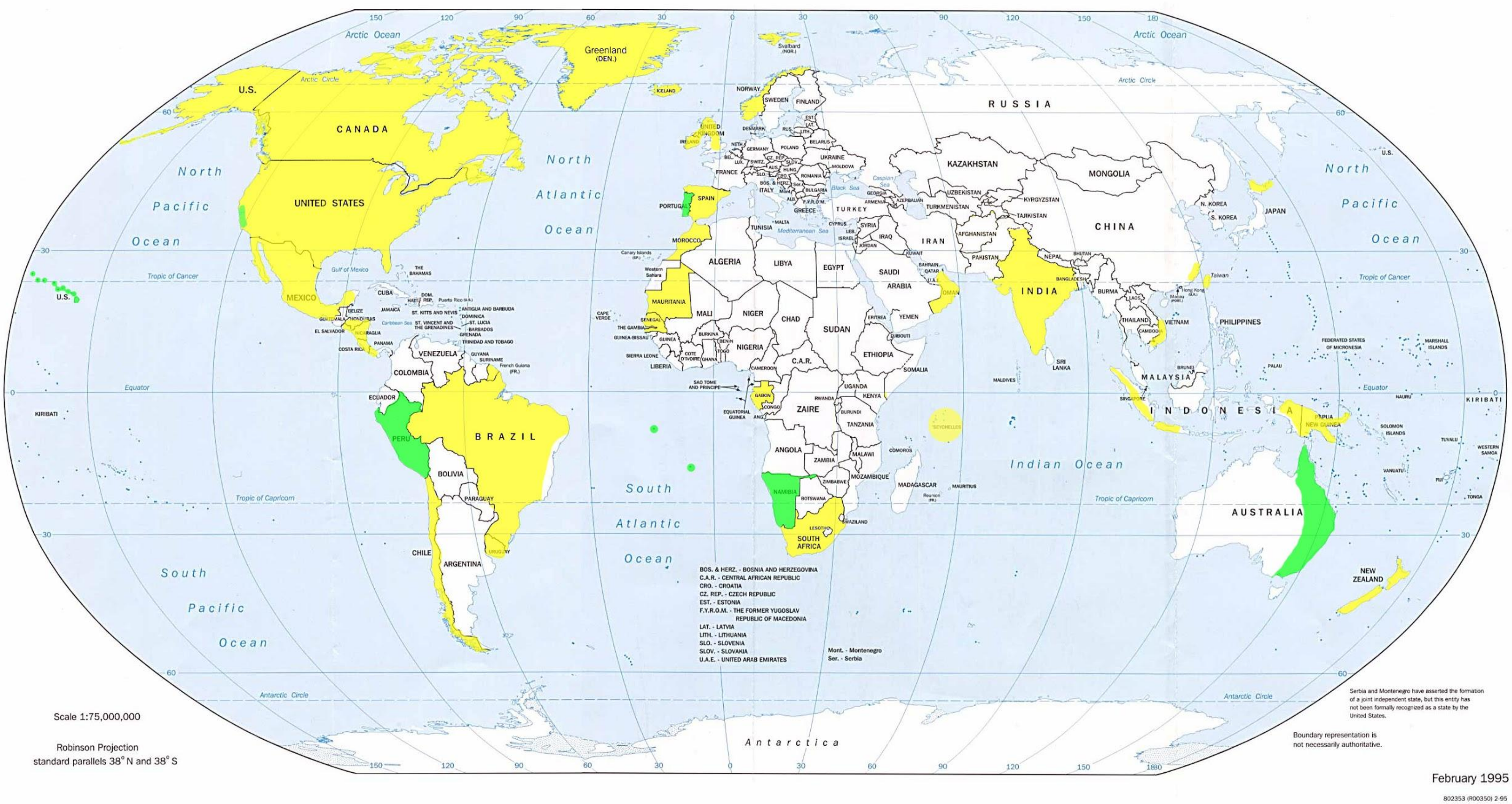
Return - Slide 78: Launch

Launch Derived Requirements

	Communications	Imaging - Visual/NIR	Imaging - Thermal
Satellite Mass (kg)	13	75 or 215	75
Injection Orbit	625 km Elliptical	567 km Sun-Synch Circular	
Satellites per Plane	3	20 or 10	4
Number of Planes	2-5	4	1

Back: Launch Requirements

All Possible Launch Locations



[Back - Pre Launch]

Payload

- Satellites want to minimize ejection velocities
  - Rotational, positional, tumbling

- Direction of deployment consideration
  - Affects sat configuration on LV
  - Small ejection velocities make direction negligible

- 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

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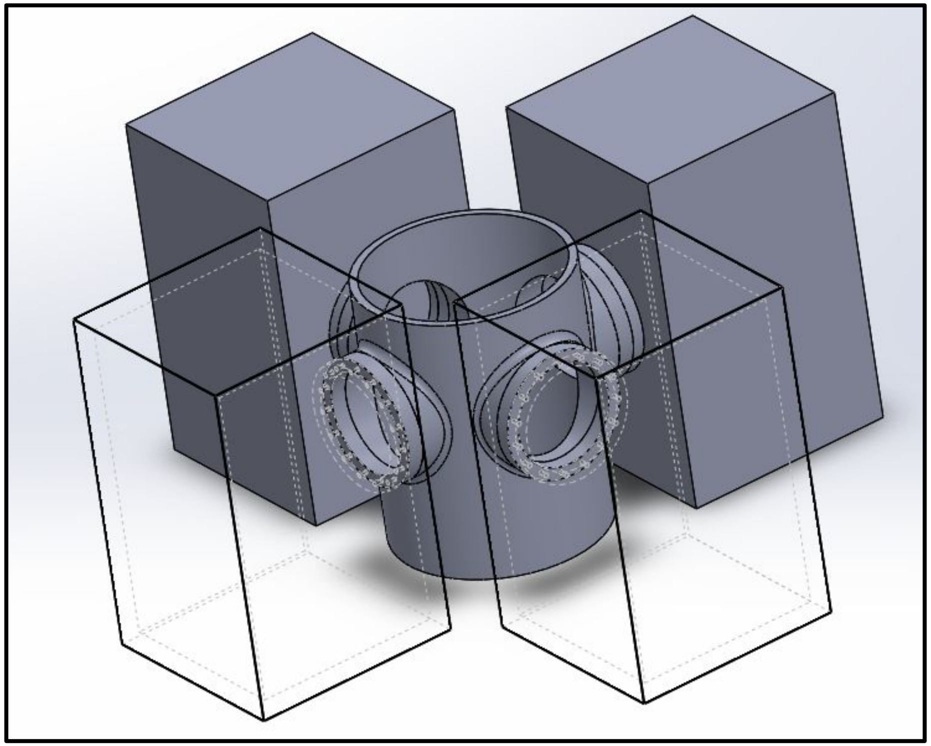
Radial Payload Configuration

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



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Launch Configuration

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ΔV Breakdown (km/s)

	Delta-V (km/s)
Stage 3	4.26
Stage 2	3.61
Stage 1	3.61
Totals	**10.97**

Mass Breakdown

***Assuming 0.1 mass fraction per stage**

ACS Thruster

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Performance Characteristics	
Operating Media	GN_2, Xenon, CF_4
Operational Temperature	-35ºC to +95ºC
Operating Pressure	1.5 to 2.5 bar
Coil Resistance	To suit Customer Power Requirements
Opening/Closing Response	<5 msec
External Leakage	1 x 10^{-6} scc/GHe
Internal Leakage	1 x 10^{-4} scc/ GHe
Operating Voltage	24-32 VDC
Cycle Life	1,500,000
Impulse Bit Repeatability	<5%
Vacuum Thrust	10mN (± 5%) to 50mN (± 5%)
ISP (Ambient Temperature	GN_2 - 72s (Nom); CF4 - 47s (Nom)
Thrust Vector Accuracy	<1º
Mass	<60g depending on interfaces
Integral Filter	12 - 35 micron (abs) - per Customer Requirement

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Conceptual Control Design