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: Adrian Williams

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 after 6 months at End-of-Life
- The system cannot be deployed in orbit prior to time of command
- The constellation must deorbit of within 5 years of mission completion

Mission Requirements

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: Adrian Williams

Mission-Level Trades

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

Mission-Level Trades

Orbital Altitude

Major Considerations	Result
• Time to orbit • Radiation concerns • Resolution requirements • Deorbit in less than 5 years	LEO

Mission-Level Trades

Satellite Capability Allocation

Major Considerations	Result
● Coverage and pass time requirements ● Satellite complexity ● Different optimal orbital schemes	Separate Communications and Imaging Satellites

Mission-Level Trades

Orbital Variability on Day of Launch

Major Considerations	Result
• Number of satellites • Number of orbital planes • Launch site location • Excess coverage	Variable

Mission-Level Trades

Imaging Satellite Distribution Scheme

Major Considerations	Result
• Time allocated for distribution • ΔV required to complete distribution burns • Maneuvering capability allocation	LV will complete RAAN spacing and true anomaly correction

Mission-Level Trades

Communications Satellite Distribution Scheme

Major Considerations	Result
• Mass of the vehicles • ΔV required to complete distribution burns • Complexity of the maneuvers	LV will place communications satellites in phasing orbits; satellites will complete the final phasing maneuver

Mission-Level Considerations

Launch Vehicle Type

Design Consideration	Result
• Time to launch • Storability • Number of satellites per launch vehicle • Reliability • Orbit configuration	Small Rapid-Response LV

Mission-Level Trades

CAL POLY
SAN LUIS OBISPO

Imaging Spectral Band Allocation

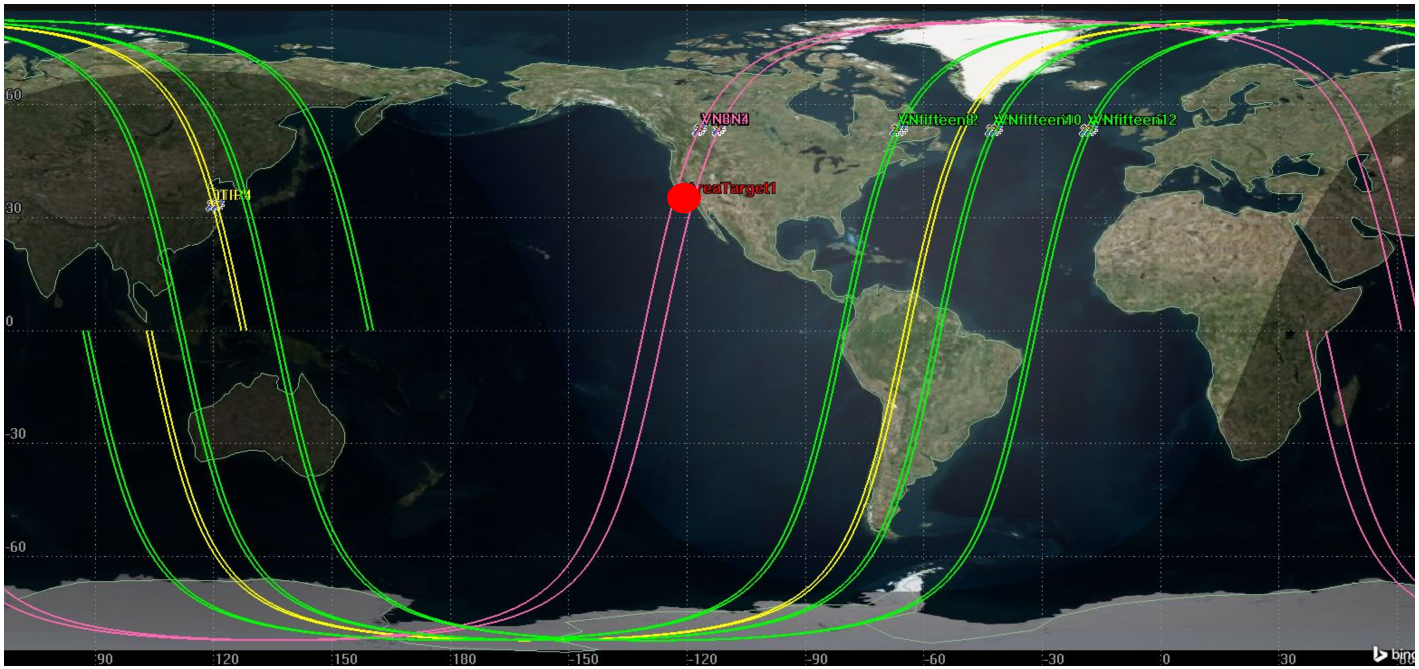
Design Consideration	Result
• Necessity for thermal imaging will be decided day of launch • Required support systems • Number of launches • Coverage requirements	Vis/NIR separate from TIR

System Architecture

Presenter: Carmelle Koren

Imaging Architecture

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

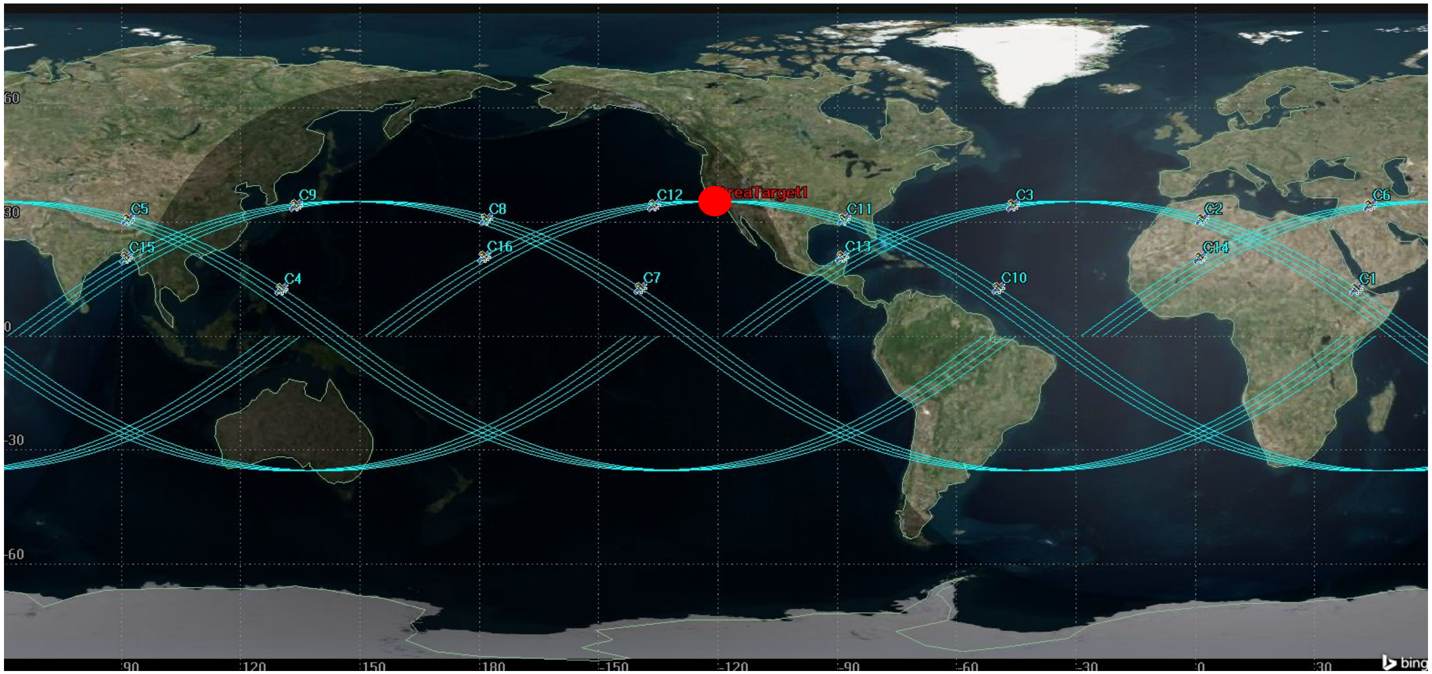


***RED** = Target Area*
***PINK** = Full Image Vis/NIR*
***GREEN** = 15% Vis/NIR*
***YELLOW** = 25% Image TIR*

- **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

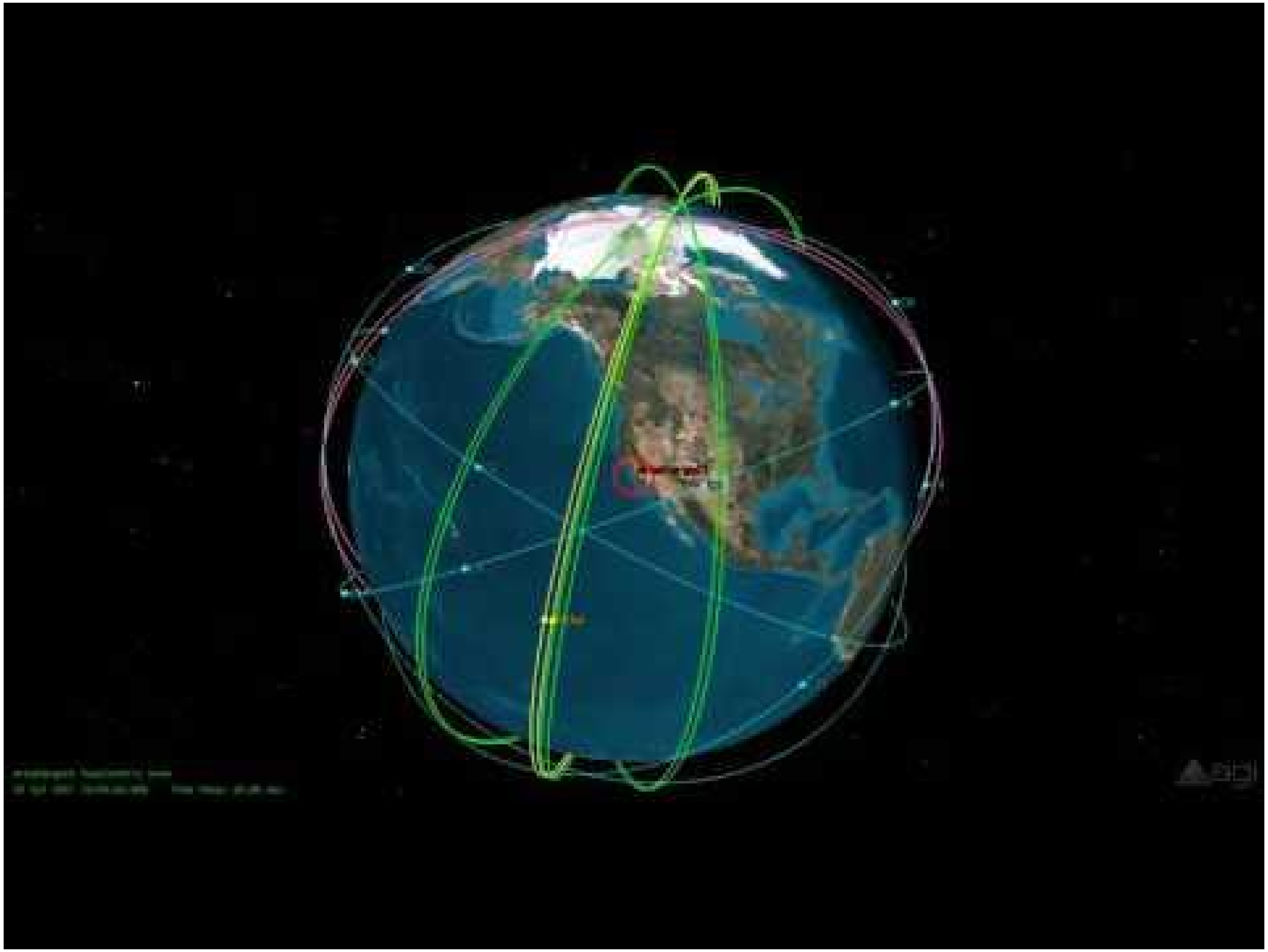


RED ***= Target Area***
BLUE ***= Satellite Ground Tracks***

- **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***

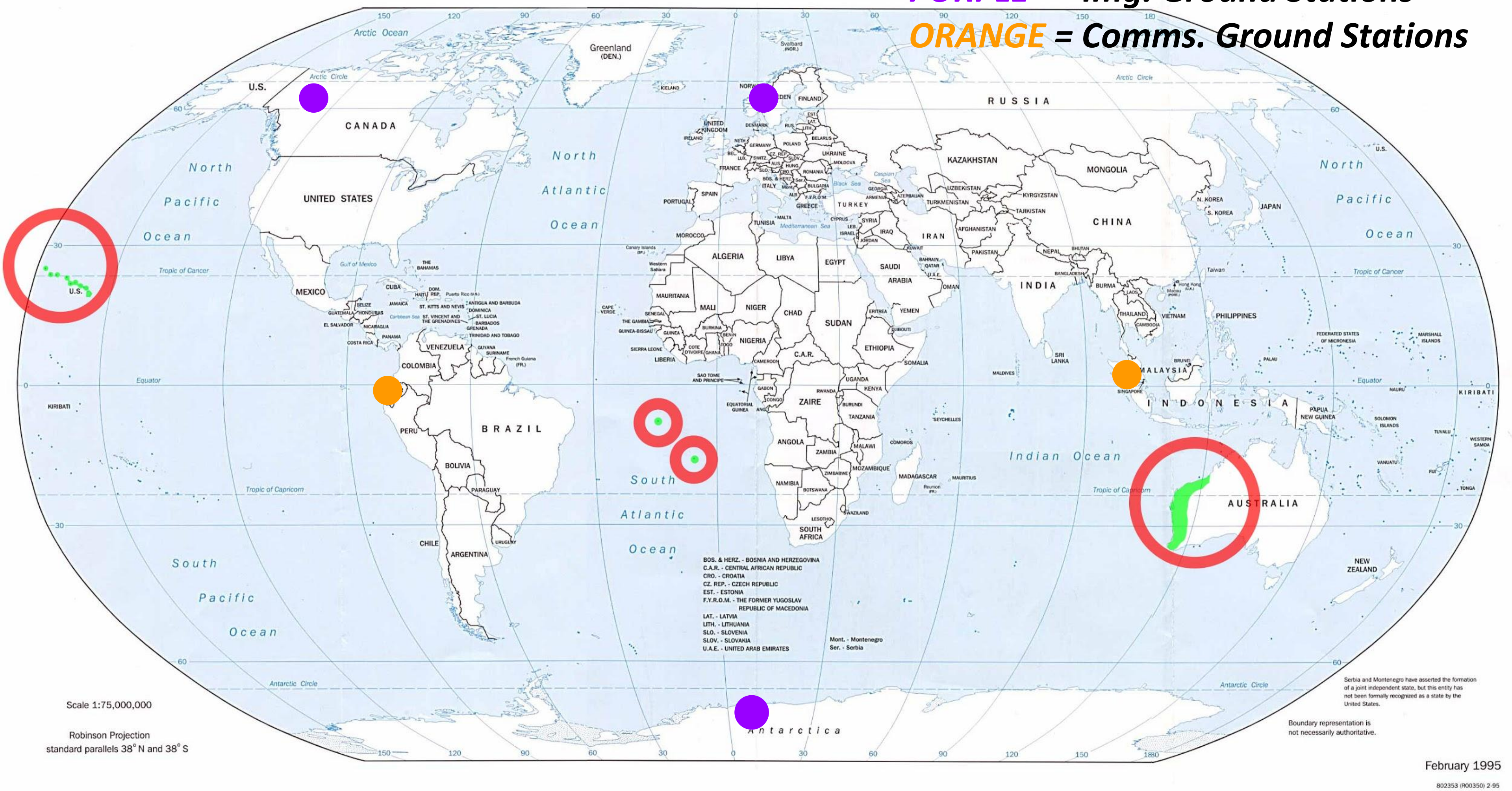
GREEN ***= 15% Vis/NIR***

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

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

Ground Operations Locations

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



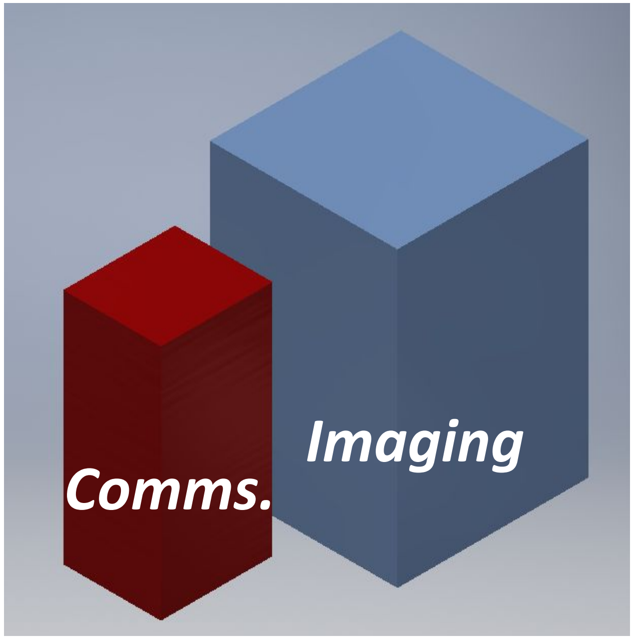
[Slide 122: All Possible Launch Locations]

System Summary

Totals

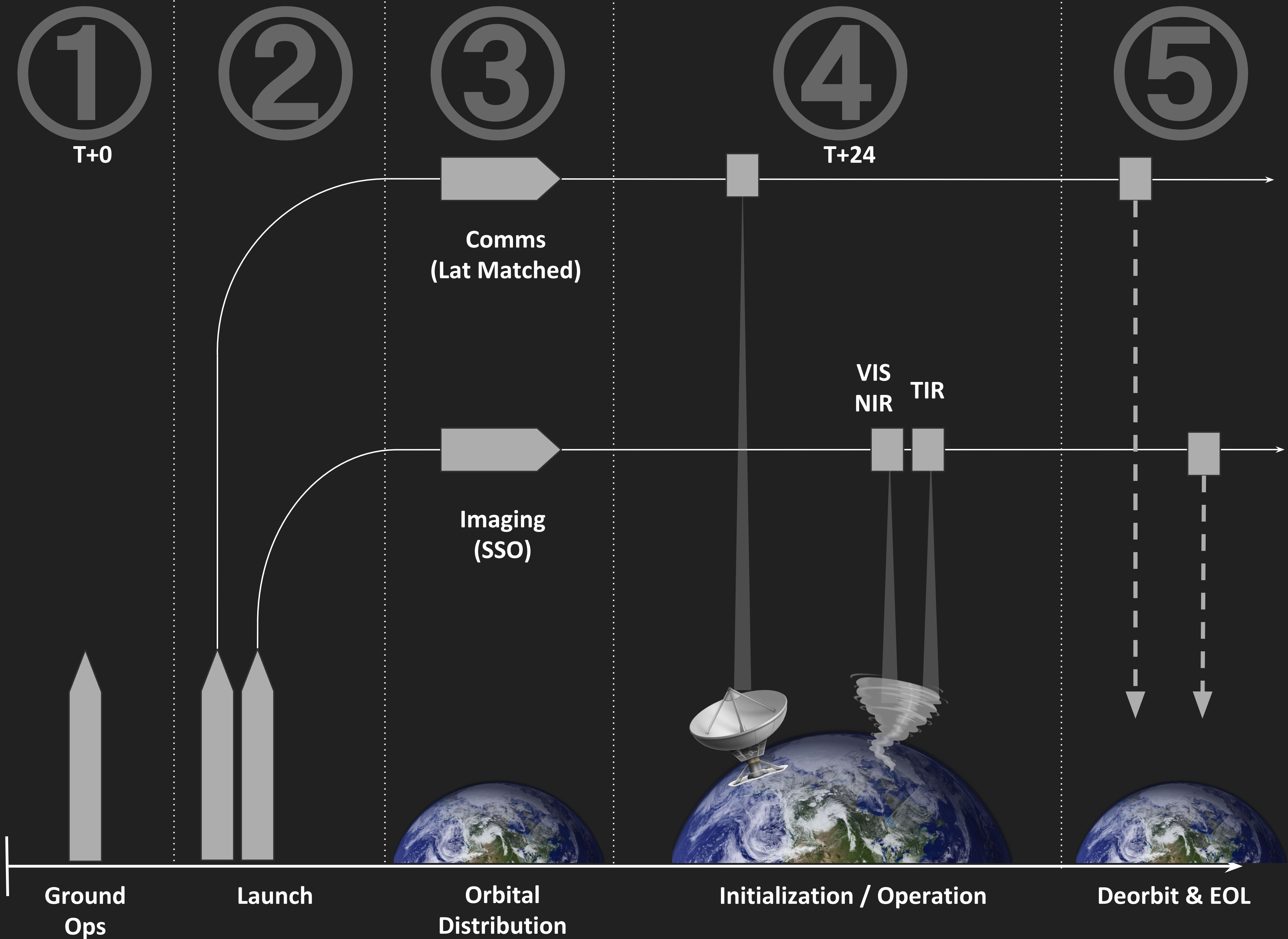
- 40 satellites
  - 24 imaging satellites in 10 planes
  - 16 communications satellites in 4 planes
- 4 launch sites, 10 launches
- 5 ground stations

	Imaging Satellites	Communication Satellites
Mass (kg)	9.5	7.5
Dimensions (cm)	28x27x42	16x14x34
Volume (m^3)	0.032	0.0076

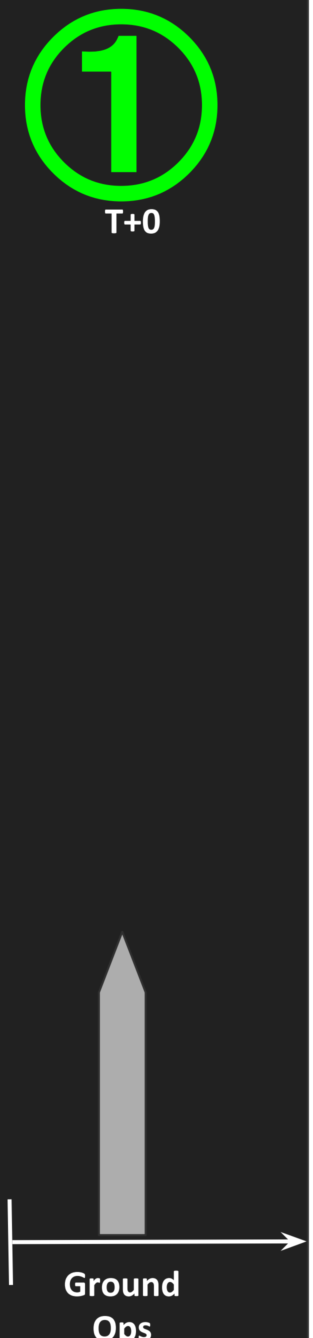


Concept of Operations

Presenter: Carmelle Koren

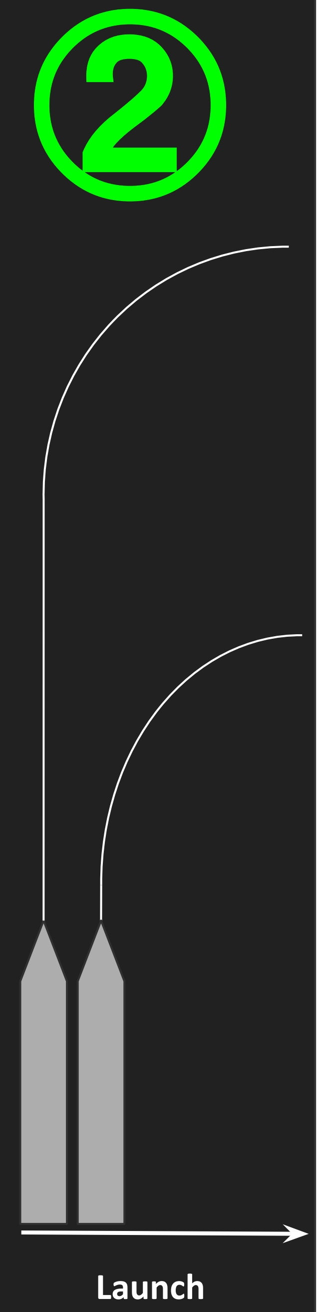


①
②
③
④
⑤
T+0
T+24
Comms
(Lat Matched)
VIS
NIR
TIR
Imaging
(SSO)
Ground
Ops
Launch
Orbital
Distribution
Initialization / Operation
Deorbit & EOL



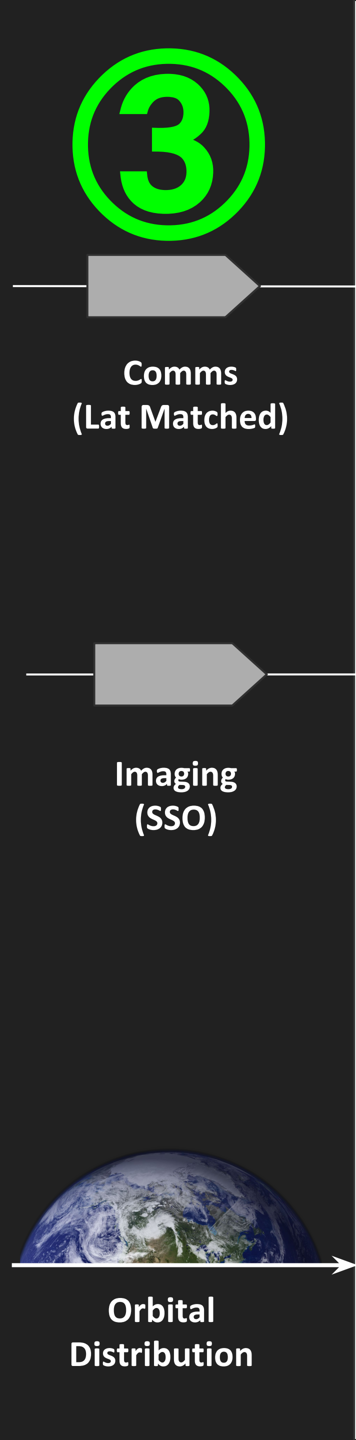
Ground Operations

- 5 years minimum storage
- Program trajectories
- Launch vehicle integration assumptions
    - Fully integrated satellites and propellant



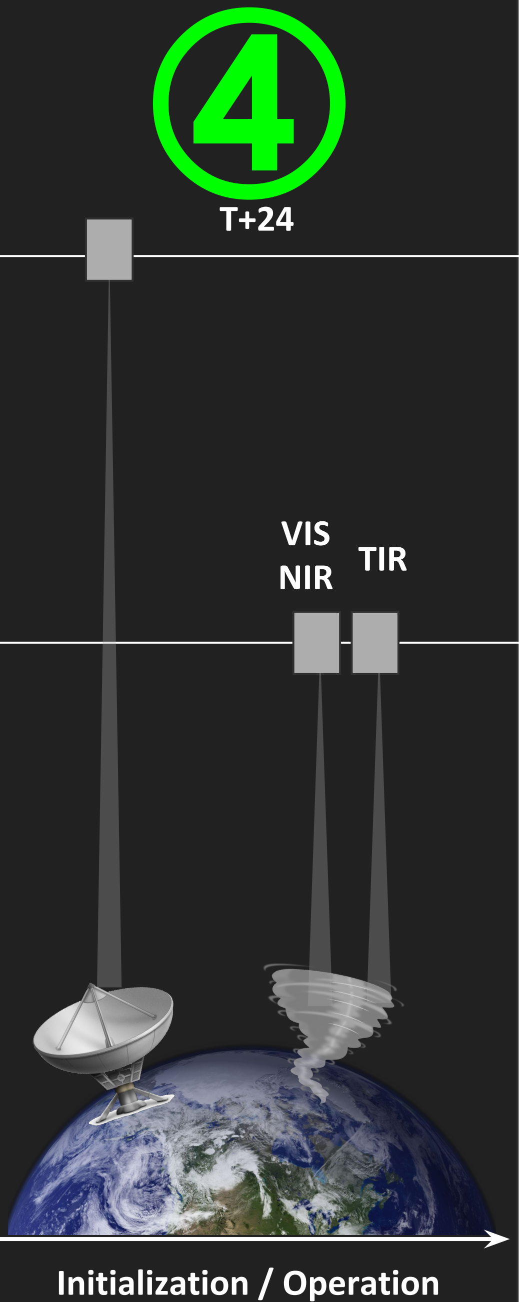
Launch

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



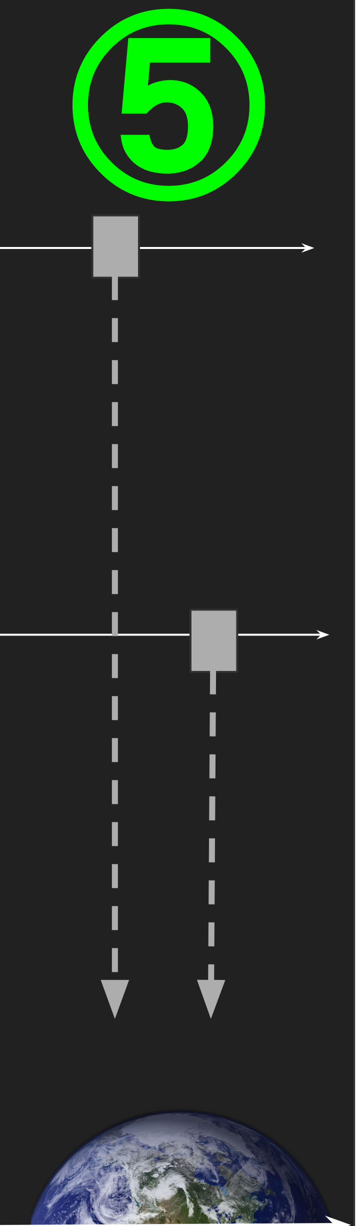
Orbital Distribution

- Imaging
  - Burn once to phase
  - Burn once to change RAAN for 15% and 25% images
- Communications
  - Burn every 3 orbits to circularize



Initialization/Operation

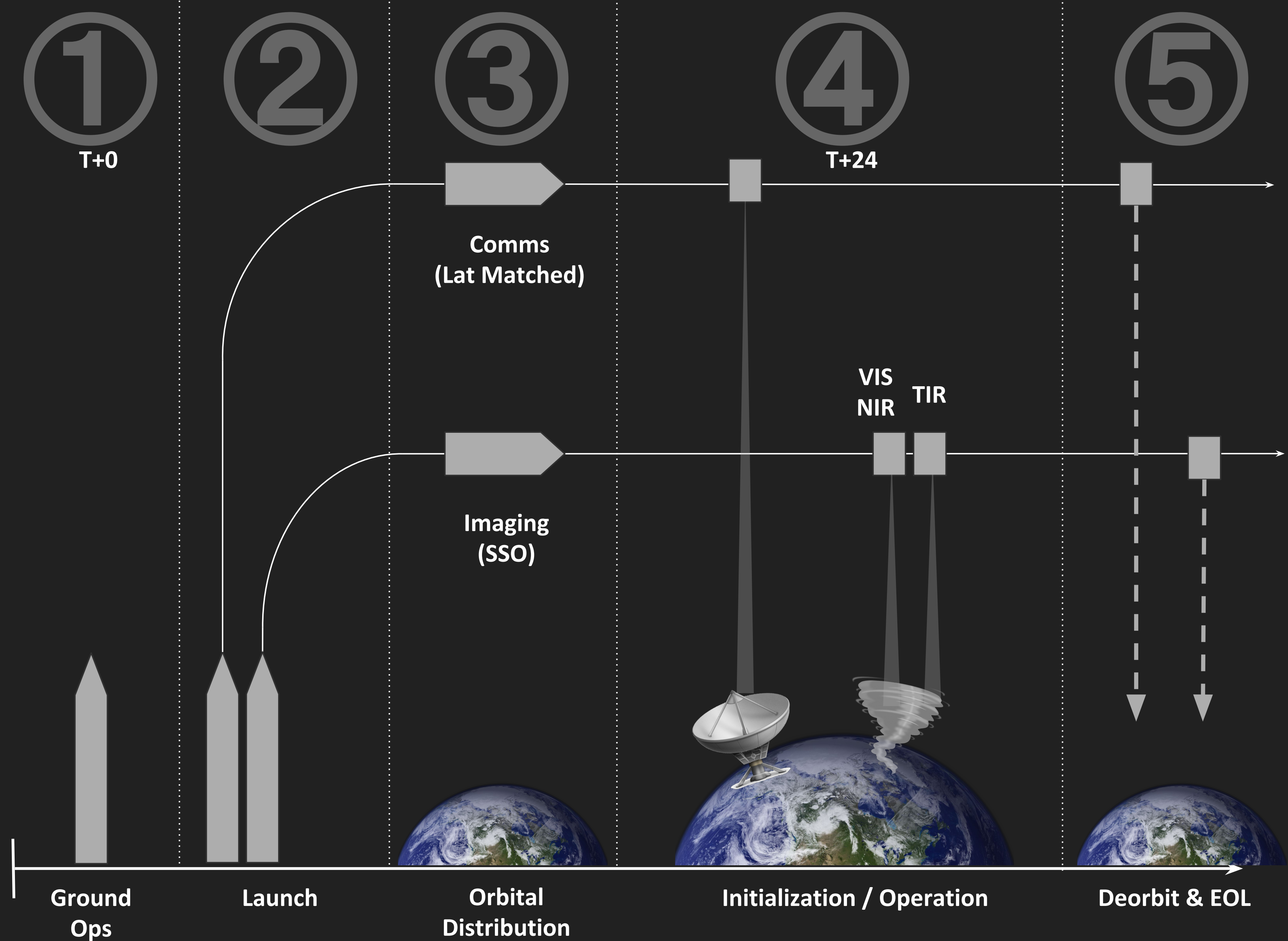
- Satellites conduct daily operations to fulfill requirements
  - Communications provide repeater access
  - Imaging receive commands and image designated areas



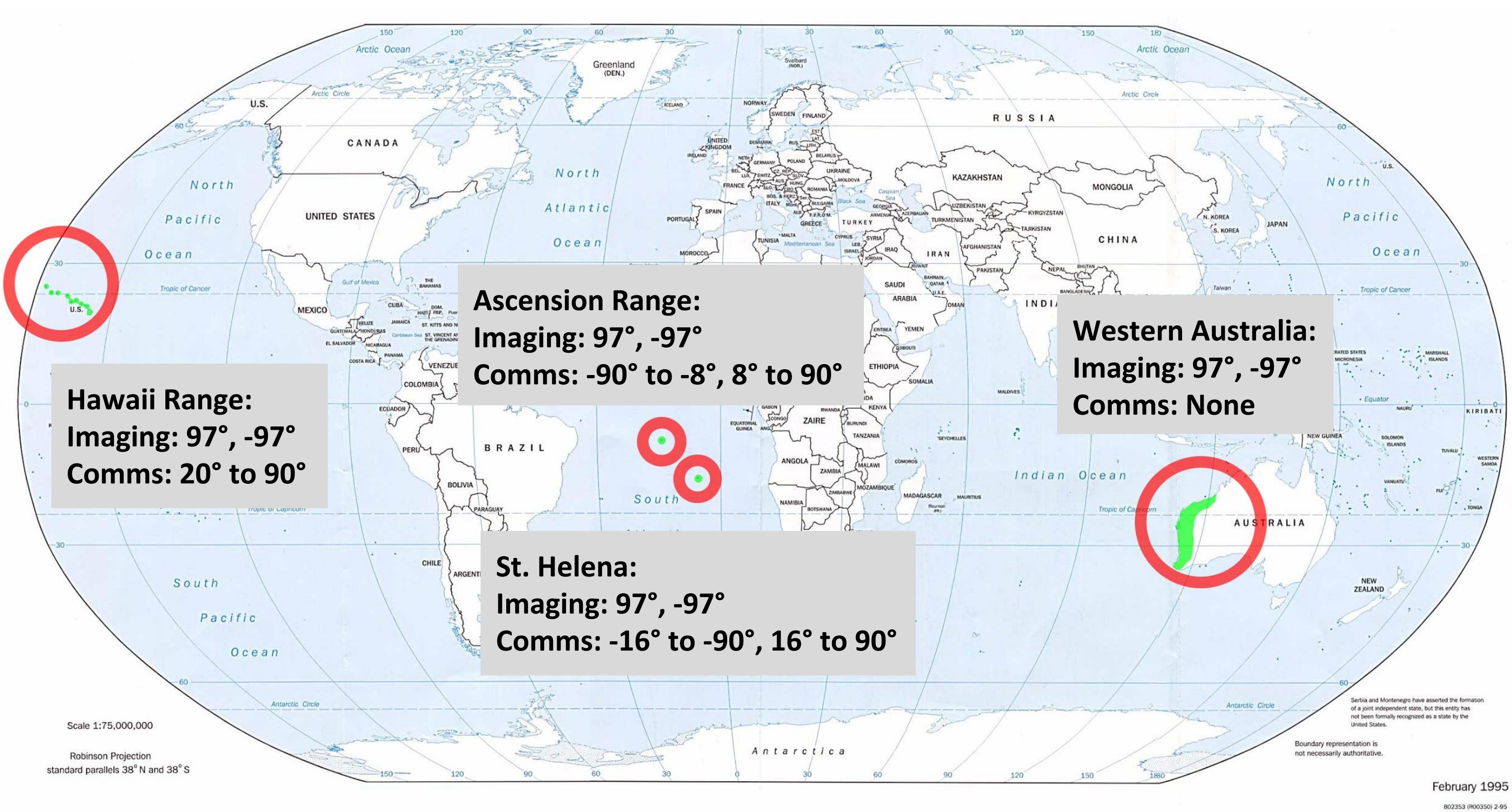
Deorbit & EOL

Deorbit & End of Life

- Satellites burn to drop altitude to deorbit within the 5 year requirement
  - Imaging sats drop to 500 km
  - Communications drop 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

Launch Locations and Capabilities



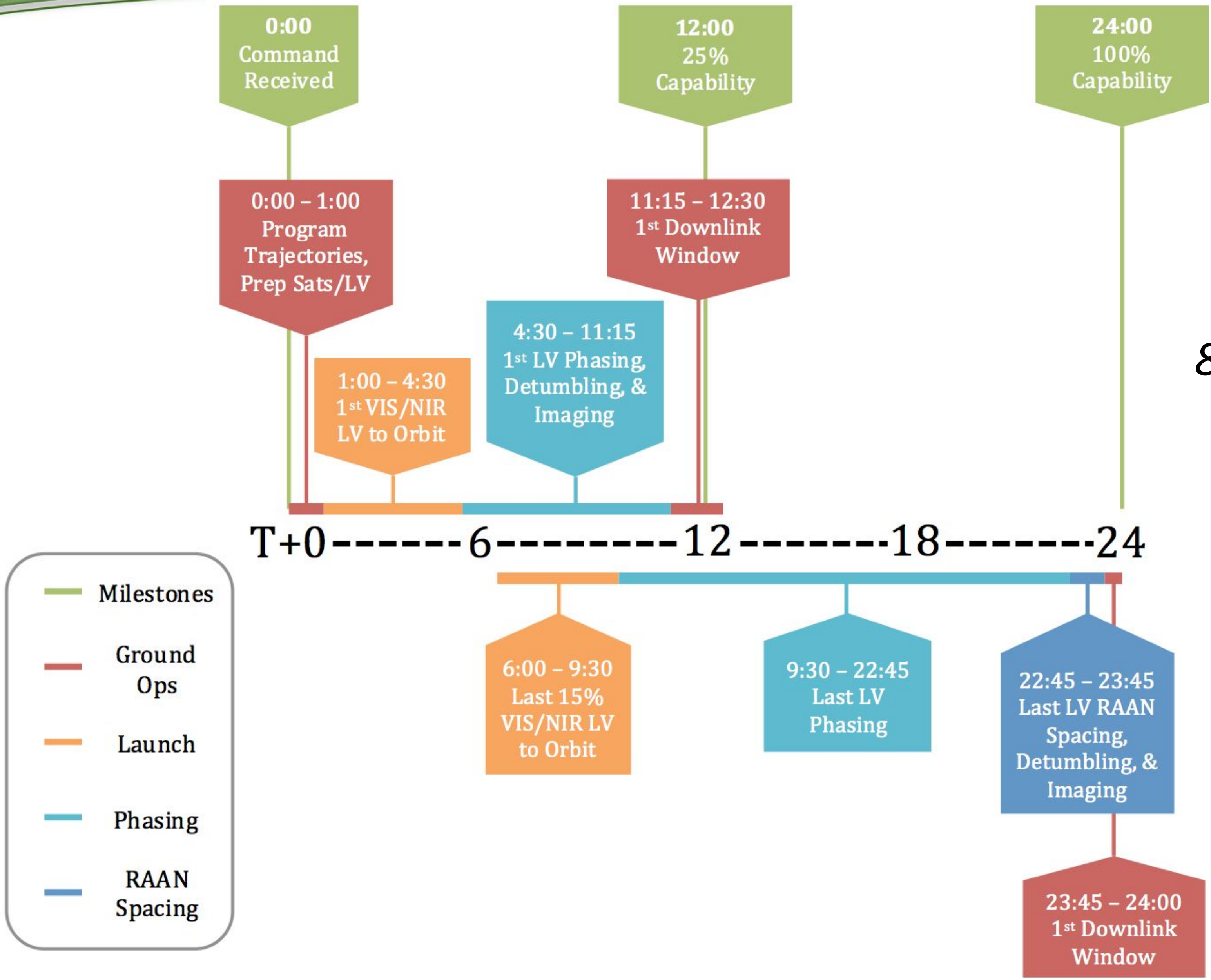
Hawaii Range:
Imaging: 97°, -97°
Comms: 20° to 90°

Ascension Range:
Imaging: 97°, -97°
Comms: -90° to -8°, 8° to 90°

St. Helena:
Imaging: 97°, -97°
Comms: -16° to -90°, 16° to 90°

Western Australia:
Imaging: 97°, -97°
Comms: None

Imaging 24-Hour Timeline



MAIN PLANES

8 satellites

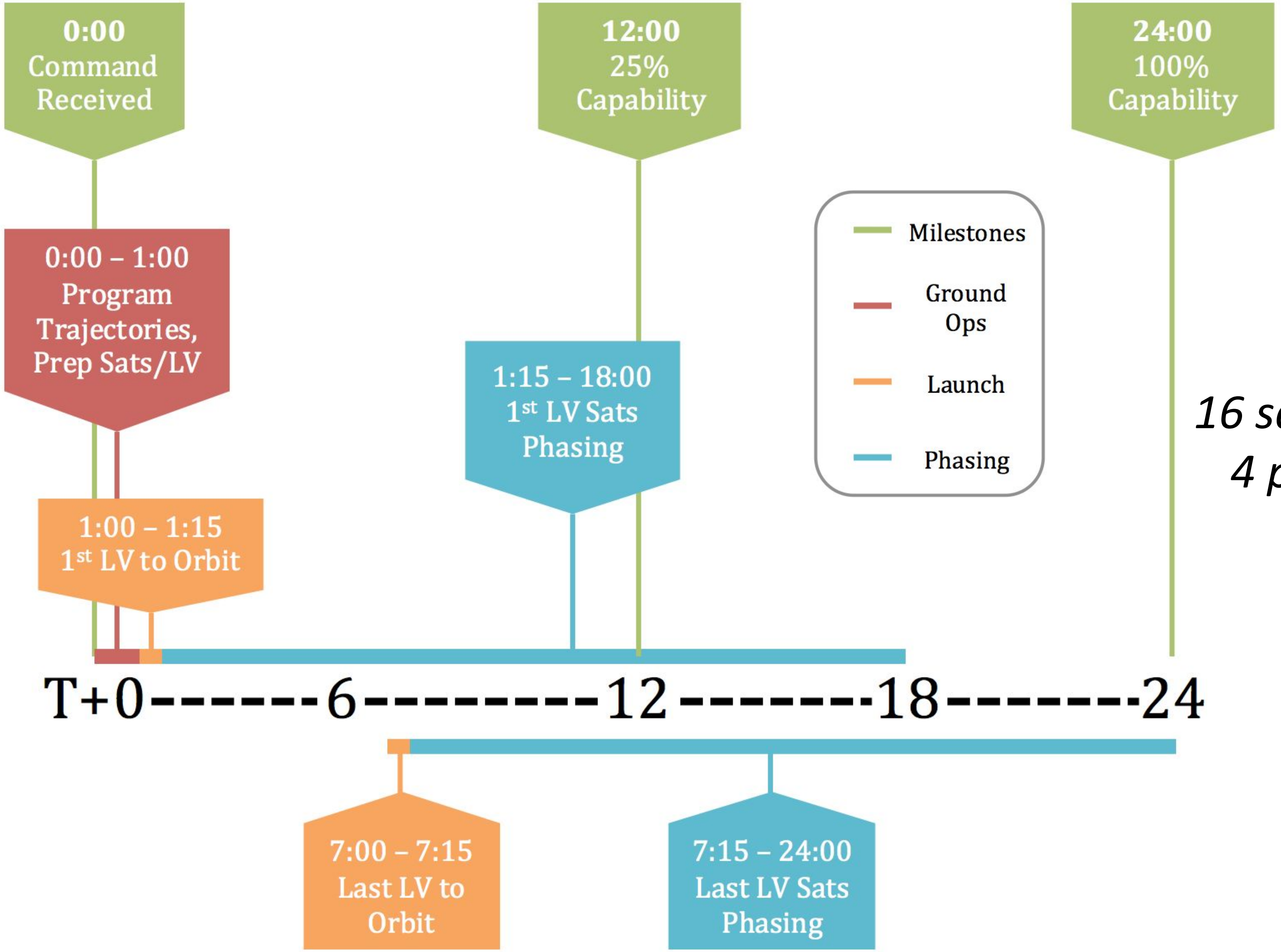
2 planes

AUXILIARY PLANES

16 satellites

8 planes

Communications 24-Hour Timeline



16 satellites
4 planes

Imaging Constellation

Presenters:
Andrew Meyer
Derek DeNardo

Imaging Constellation

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, correcting perturbation
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	Reaction Wheels

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

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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°		90°
No. of Planes	8	2	2
Total No. of Satellites	20	8	8

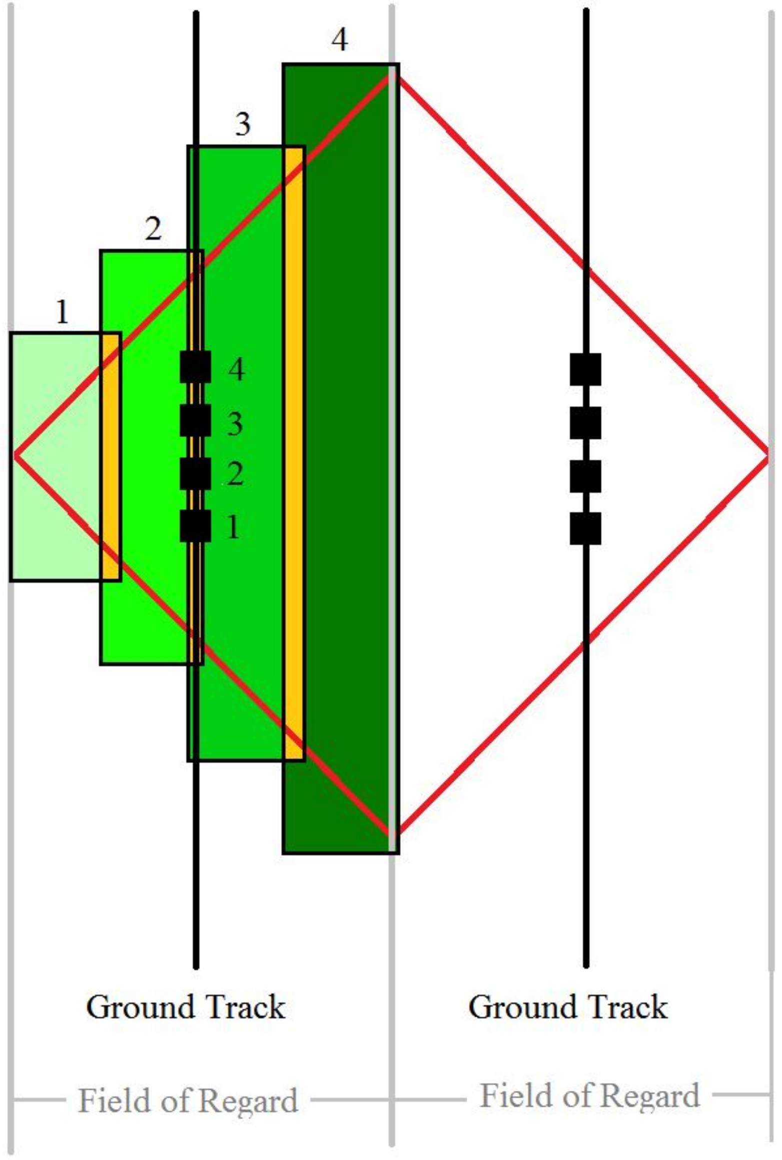
Imaging Constellation

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

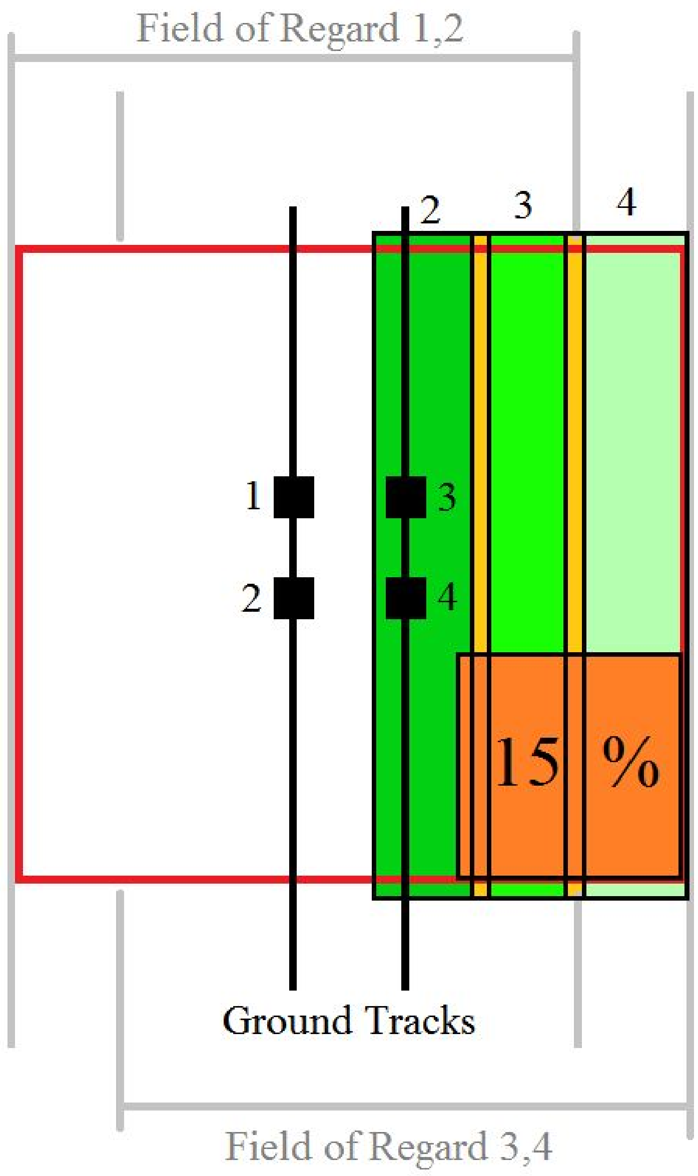


VIS/NIR Imaging Scheme

Pushbroom Scanner

15% Groups:

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



Imaging Constellation

Orbital Scheme: Thermal IR

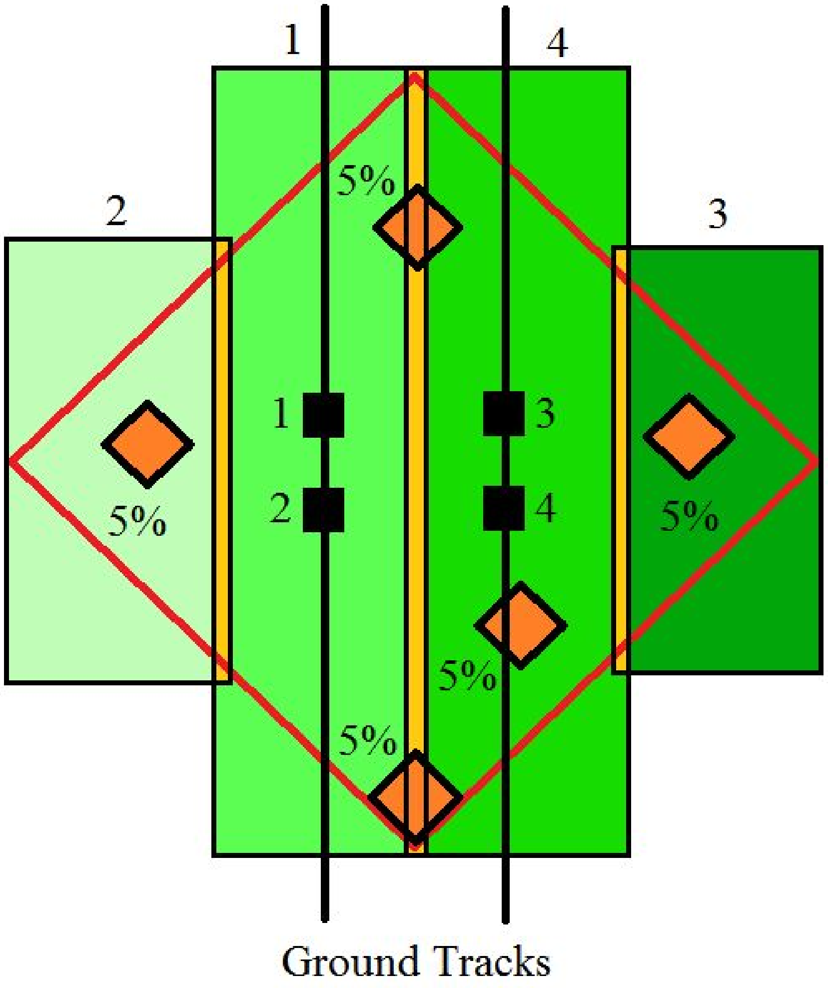
Latitude	**0° - 80°**	**> 80°**
Orbit Type	Sun-Synchronous Repeat Ground Track	Polar Repeat Ground Track
Altitude	567 km	554 km
Inclination	97.7°	90°
No. of Planes	2	
Total No. of Satellites	4	

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

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Satellite Maneuvers Summary

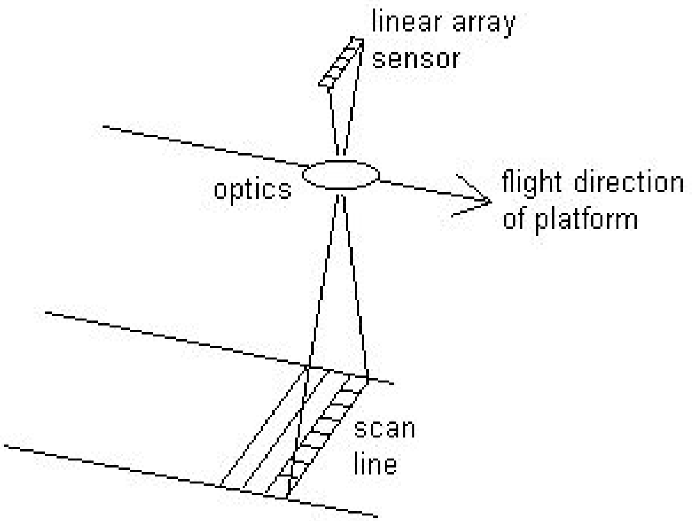
- On-orbit station-keeping
- De-orbit in 5 years after 6 month lifetime
- SSC 1 N Monopropellant Thruster
- High Performance Green Propellant (LMP-103S)
- ΔV budget

Maneuver	Stationkeeping	De-Orbit	Total
Required ΔV	75 m/s	18 m/s	93 m/s

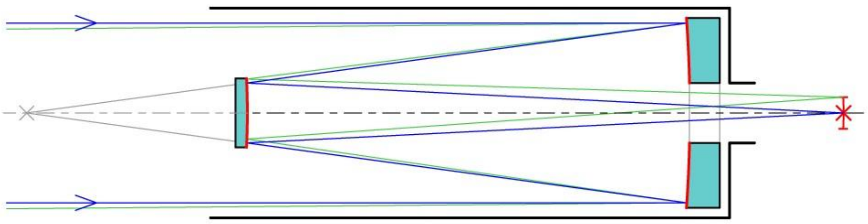
Slide 119: Liquid Monopropellant Trade

Optical Payload

- Pushbroom sensor
    - Linear sensor array
- Reflecting telescope
    - Cassegrain design
    - Same optics for both Vis/NIR and TIR
    - ∅18cm x 40cm allocated space
- Number of Detector Elements
    - Vis/NIR: 22,000 x 6 bands
    - TIR: 4,300 x 6 bands



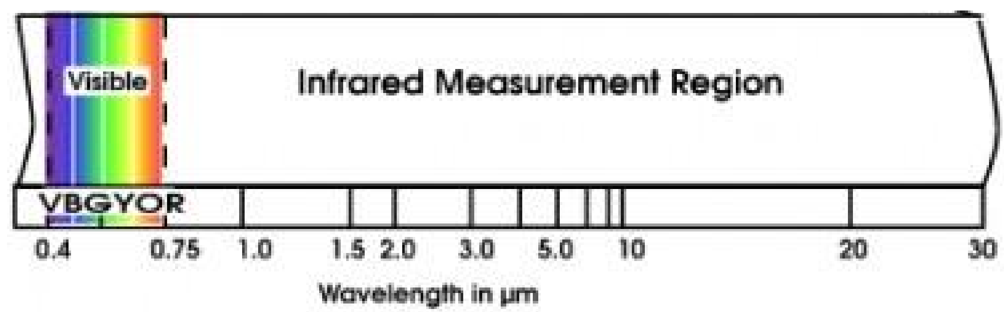
Cassegrain-Telescope



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



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, 4.5 x 5.5 x 10.9 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	13 dB
Power (RF)	20 W
Margin	3.3 dB

Imaging Constellation

Imaging Satellite Communications

On-board system for TT&C:

- UHF band
- Monopole whip antenna on-board, 20 cm length
- BPSK modulation

Ground system for TT&C:

- Utilizing same ground dish for imaging downlink and TT&C
  - 14.7 dB peak gain for UHF

TT&C Link Budget	Downlink	Uplink
Frequency	300 MHz	
Noise Temp	285 K	
Space Loss	146 dB	
Signal to Noise Ratio	9.5 dB	10.5 dB
Data Rate	1 kbit/s	
Gain	-6 dB	14.7 dB
Power (RF)	0.025 W	0.03 W
Margin	10 dB	

ADCS: Actuators

- 4 Reaction Wheels and 3 Magnetorquers

- Pointing requirement for imaging: 0.3 degrees
  - Dependent on swath width

- Pointing requirement for downlinking: 7.5 degrees
  - Required to establish and maintain communication

- Max slew rate: 0.5 deg/sec
  - Derived from downlink tracking phase

- 2% settling time of 5 minutes

ADCS: Sensors

Star Tracker: 3-axis attitude knowledge

- Attitude knowledge: 0.03 degrees
  - Derived from 0.3 degree pointing requirement (industry standard)
- Fine knowledge required during imaging phase only
  - Star tracker (baseline) falls out of imaging requirements at ~1.2 deg/sec
    - Angular rate sensors under review

Imaging Constellation

Power and Mass Budgets

Total Mass: 9.5 kg

- Structure: 20% of total mass
- Optical payload estimate: 3 kg
- Propellant: 0.4 kg

Average Power Required: 10.5 W (per 1 day cycle)

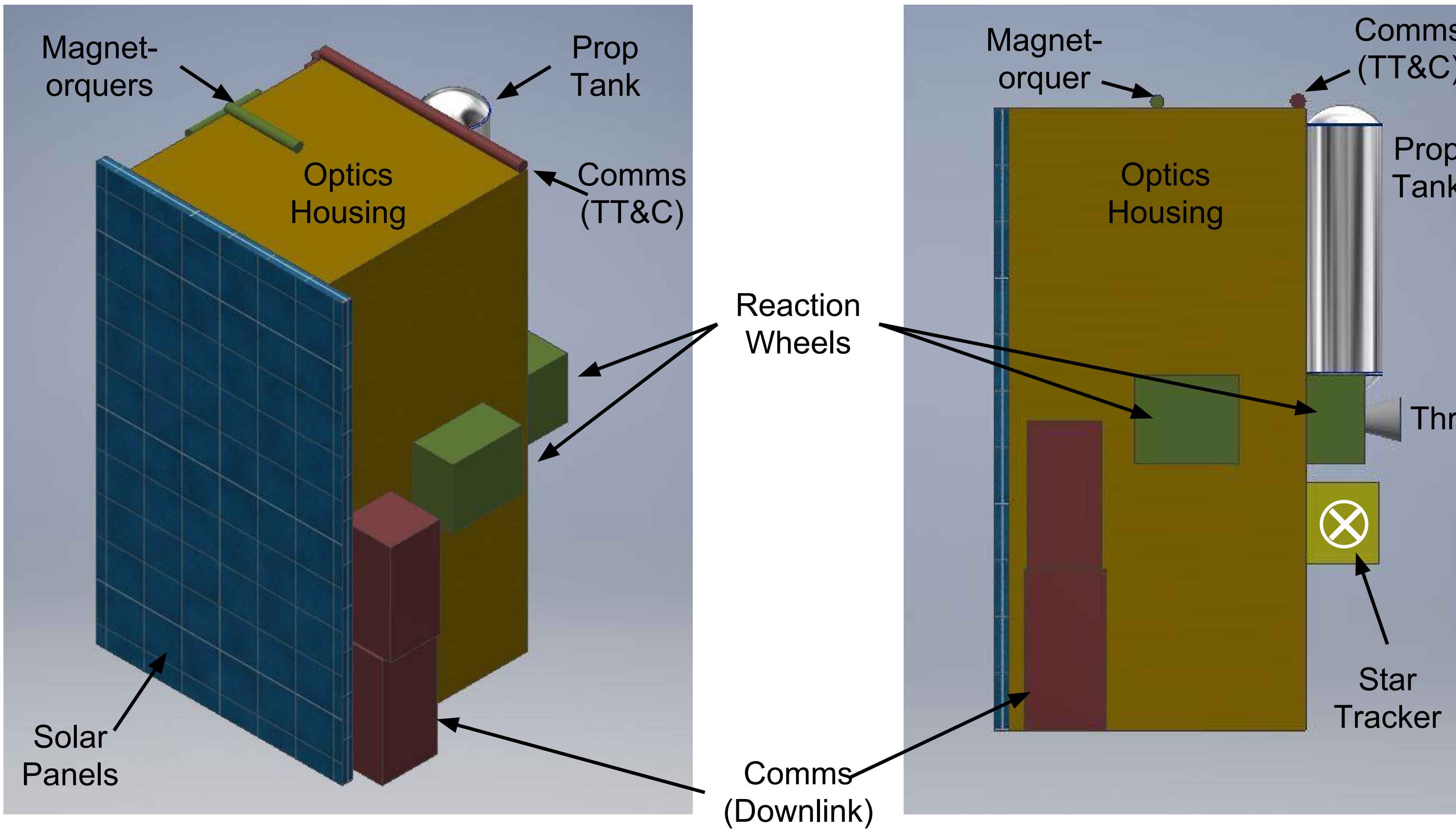
- Peak Power: 150W (imaging/calibrating) for 200 seconds
- Body-Mounted Solar Panel
- Orient spacecraft perpendicular to sunlight

Battery and Solar Panel Sizing

Imaging Constellation

S/C Mass: 9.5 kg

Dimensions: 28 x 27 x 44 cm



Imaging Constellation

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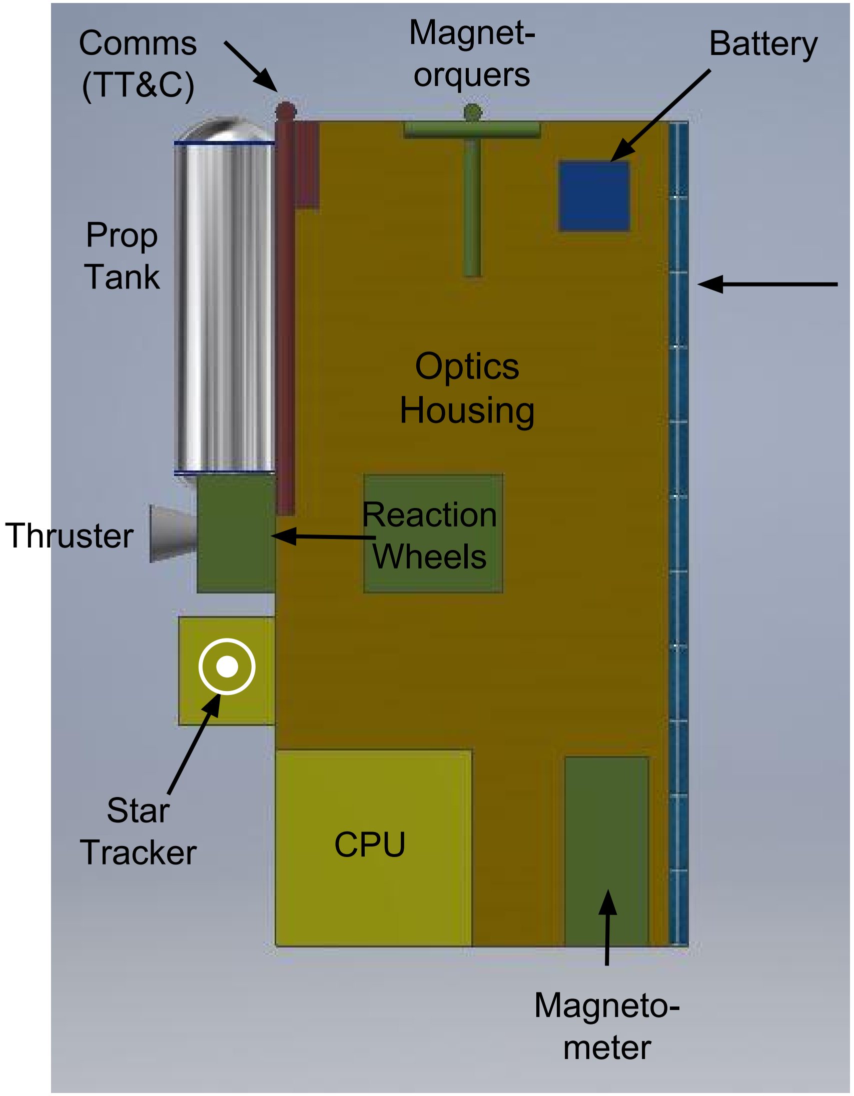
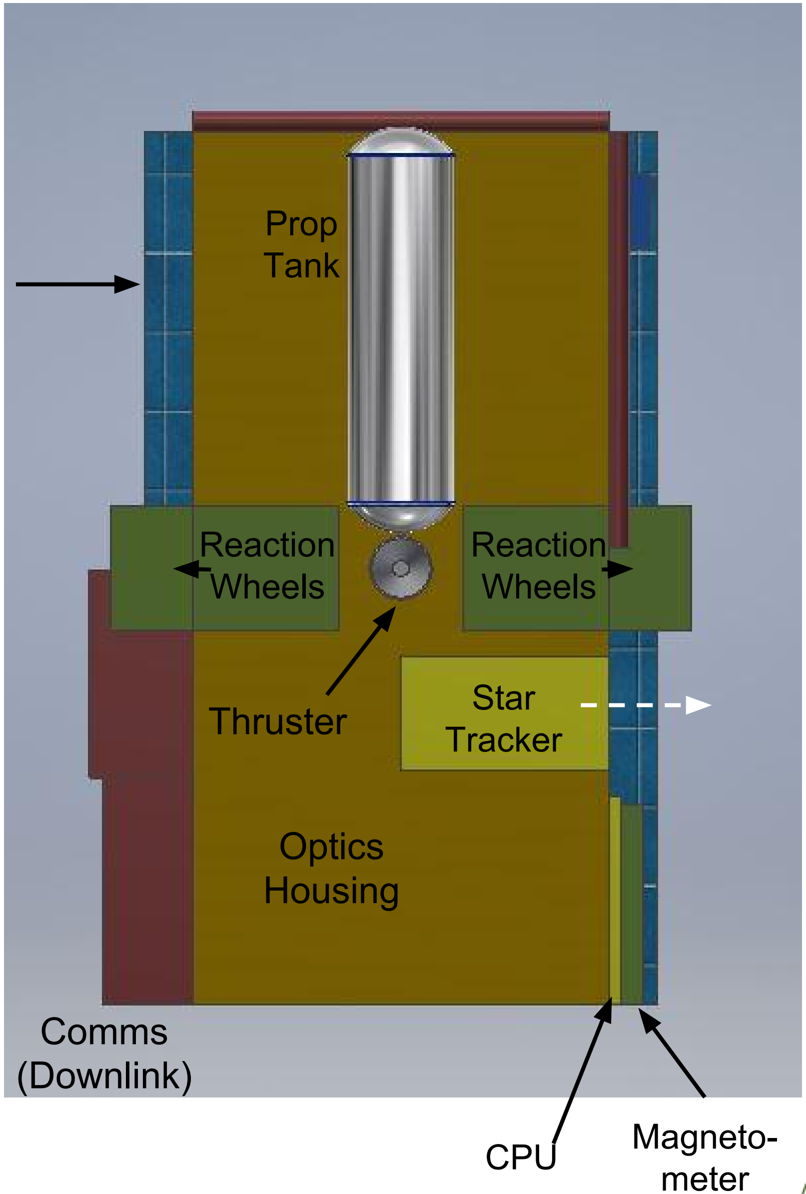


Solar
Panels



Imaging Constellation

Path Forward

- Optics
  - Cassegrain dimensions
  - Consider different telescopes for the different bands
- Specific wavelengths for bands of interest
- Focal plane assembly configuration
- Angular rate sensors
- Satellite Configuration
  - Thermal and Structural Analysis
- Thruster requirements and selection
- Redundancy and Failure Mitigation

Communications Constellation

Presenter:
Alex Powaser

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

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

Sats/Planes Code

- 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)	Orbit Type
625 ± 7 km	Latitude ± 0.1°	Equal ± 6°	40°± 6°	Circular

Constellation Scheme vs Coverage Latitude

Latitude Bin	0°-10°*, 83-90°	10°-25°, 65°-83°	25°-65°
No. of Satellites	8	12	16
No. of Planes	2	3	4

*0-8° covered by 8° inclination from Ascension launch site

Communications Constellation

Phasing Scheme

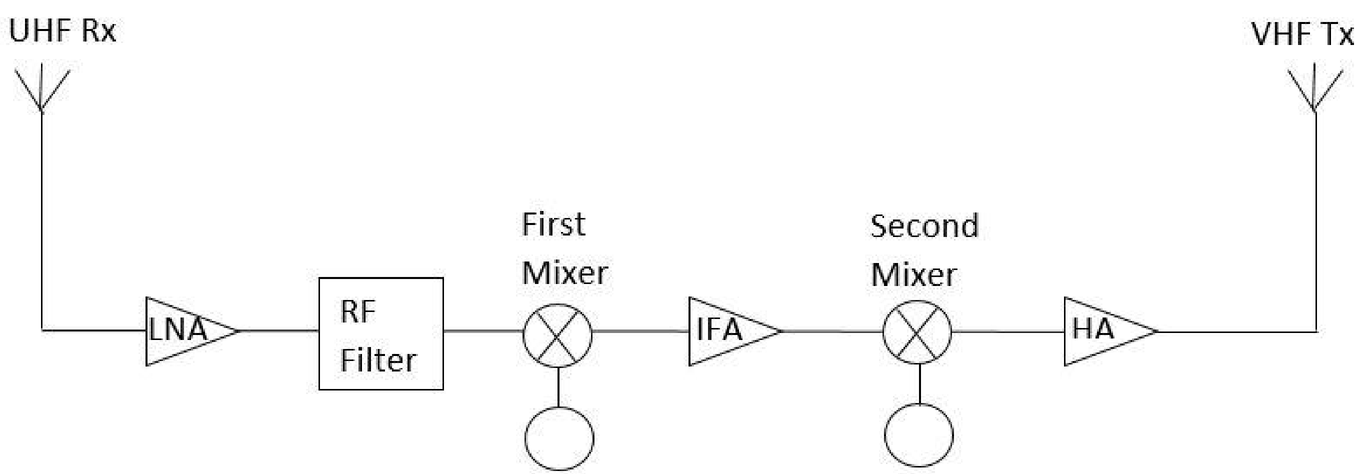
- Transfer orbit details

Semi-Major Axis	Eccentricity	Period
7175 km	0.0240	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)
  - Aerojet MPS-130 Thruster (discussed later)

Payload Design

- First responders using tactical UHF/VHF radios
  - Based on Harris XL-200P
  - UHF/VHF capability
- UHF repeater
  - UHF uplink/VHF downlink
  - 15 transceivers
    - Solid-state components
    - Frequency-Division Multiplexing (FDM) to handle channels



Communications Constellation

Link Budget	Uplink: Ground to Satellite	Downlink: Satellite to Ground
Frequency	300 MHz (UHF)	137 MHz (VHF)
Noise Temp	298 K	
Space Loss	138.5 dB	145.2 dB
SNR Required	13 dB	
Data Rate	16000 bps	
Receiver Gain	0 dB	-1 dB
Transmitter Gain	-1dB	0dB
Power (RF)	2.5 W	0.45 W
Margin	6 dB	

Link Budget

- Decisions:
  - No. of channels: 15
  - Omni-directional Antennas
    - One for each frequency
  - Antenna type: 4 monopole whips in phase quadrature

Communications Constellation

Doppler Shift and Encryption

- Doppler Shift
  - VHF max doppler shift seen by AOI: 2950 Hz
  - UHF max doppler shift seen by S/C: 6461 Hz
  - Channels spacing: 12.5 KHz

- Secure Communication
  - Only want people in the AOI to receive our communication
  - AES/DES encryption available on our baseline radio

Communications Constellation

Possible Propulsion System

- Aerojet MPS-130
  - Used for initial phasing and deorbit
  - Phasing: 90 m/s delta-v
  - Deorbit: 68 m/s delta-v
    - Drop perigee to 450 km
    - Deorbits < 5 years
  - F = 1.5 N of directed thrust
  - ISP = 240 s
  - Compact 1U and 2U Sizes
  - 3-Axis Stabilization Capabilities
  - High Performance Green Propellant

Communications Constellation

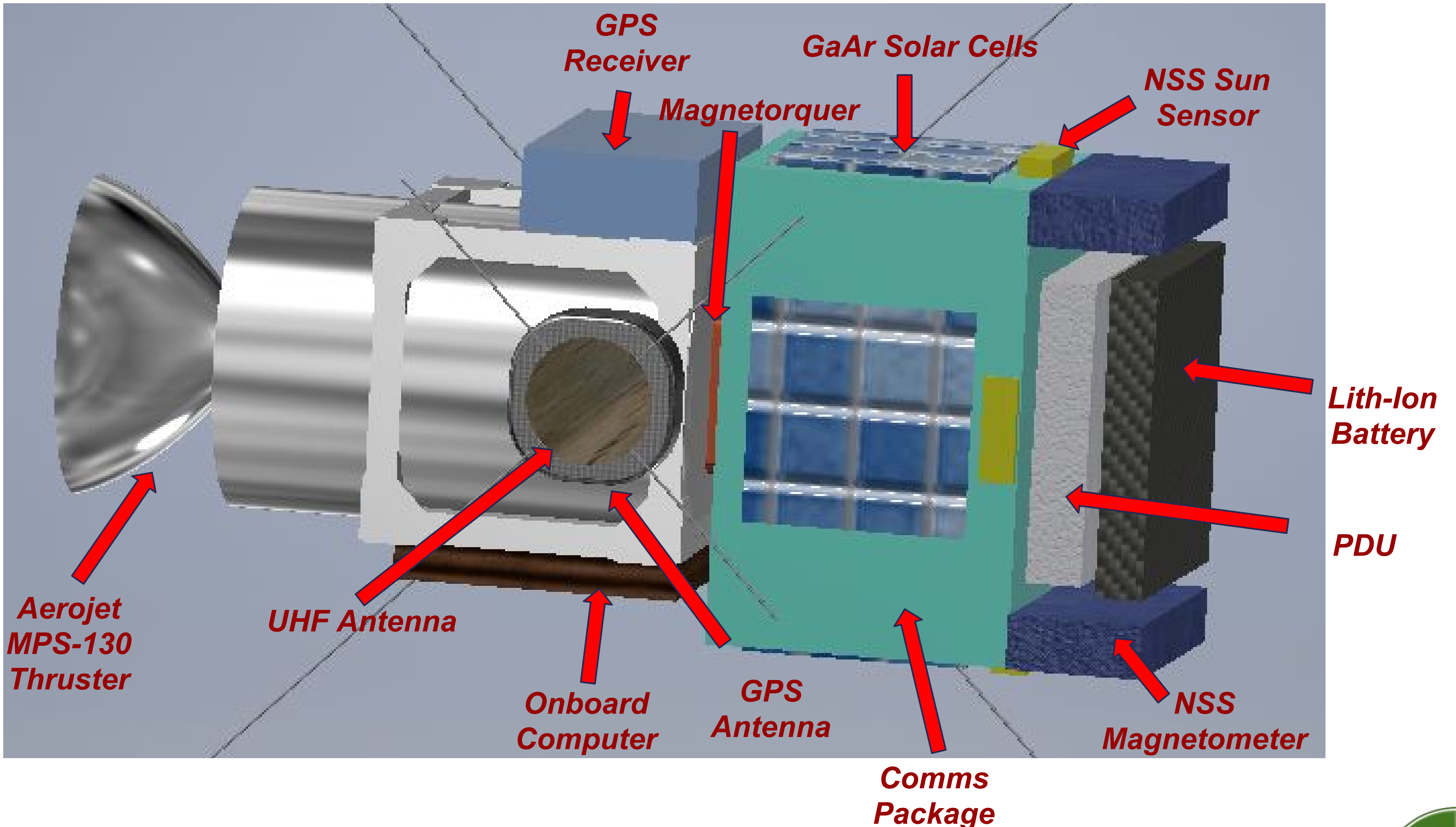
ADCS

- Thruster
- Magnetorquers
  - Detumble
  - Additional pointing for thruster
- Determination Sensor: TBD

Telemetry, Tracking, and Command

- Use existing payload antenna
  - Designated channel
- Sending/receiving health packets, coverage schedule, etc.
- Utilizing 2 communications ground stations

Configuration



Communications Constellation

Mass

- Total mass: 7.5 kg

Power

- Idle power: 5 W
  - In between comms intervals
- Communication power: 18.2 W
- Thrusting power: 35.7 W

Comms Component List
Comms
Mass-Power-Thermal

Launch

Presenters:

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Launch

Critical Considerations

- Time to launch
  - As quickly as possible from time of command to meet operational 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

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Derived Requirements from System Architecture

Payload	Imaging	Communications
Satellite Mass	9.5 kg	7.5 kg
Orbit	Circular 97 degree Sun-Synchronous	Elliptical transfer orbit Latitude-Inclination Matching

System Level Launch Vehicle Design Considerations

- Similar payload masses reduce discrepancies between ΔV requirements of different LV configurations
- *Design Goal: Ensure All Requirements Are Satisfied by 1 Launch Vehicle Design*

Major Trades

Trade	Status	Baseline
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
Individual Stage Propellants	Open	Liquid Solid
2 vs. 4 Imaging Sats per LV	Open	4

Launch Location Considerations

- Lat-matching not feasible from latitudes higher in value than orbit inclination

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

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

Ideal Imaging Launch Sites Found: ***9***
Sites Chosen: ***4***

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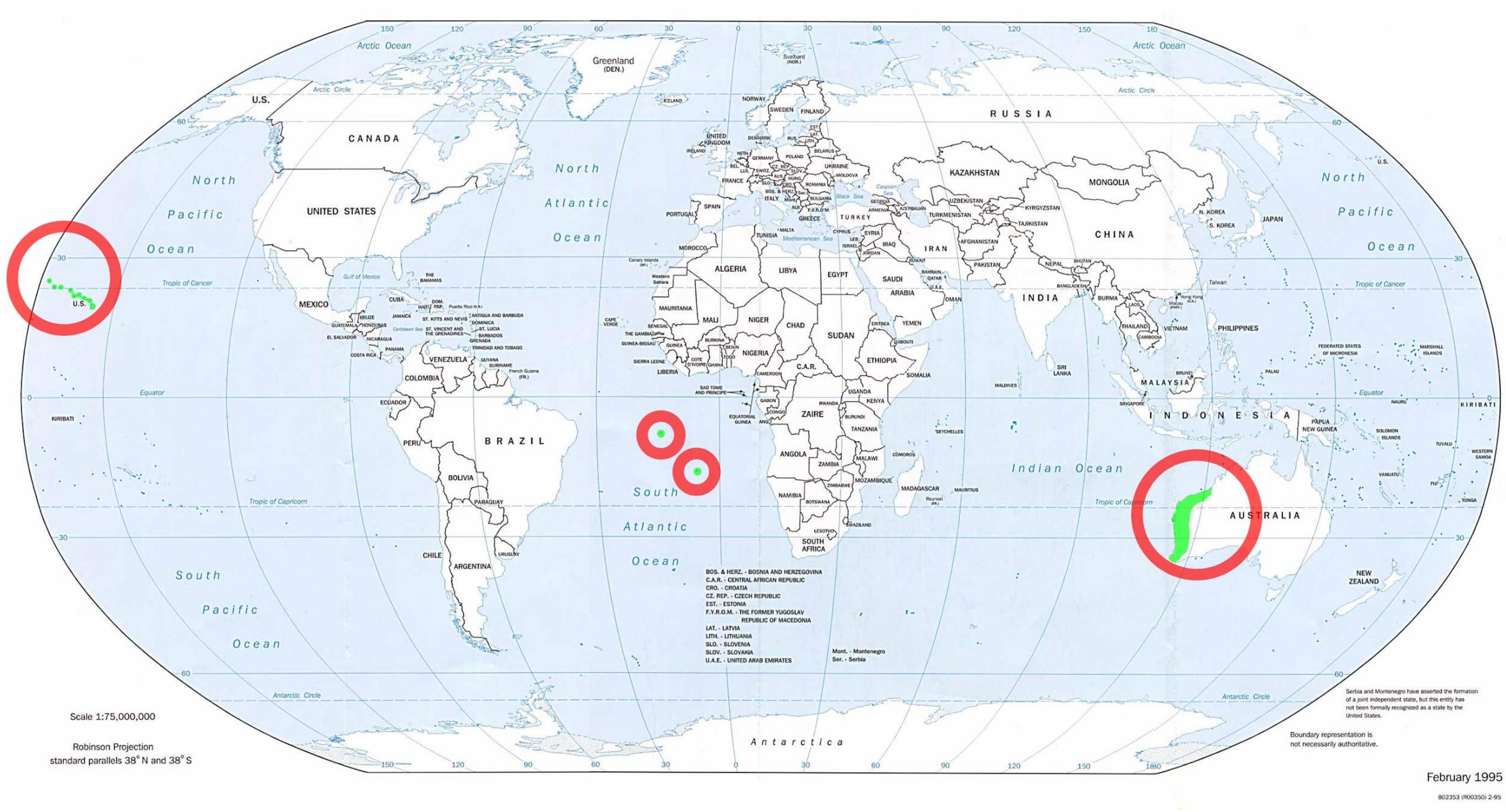
Ideal Launch Locations for our Architecture



[*Slide 122: All Possible Launch Locations*]

Launch Pad Distribution

10 total launch pads distributed amongst 4 major launch sites

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

Launch

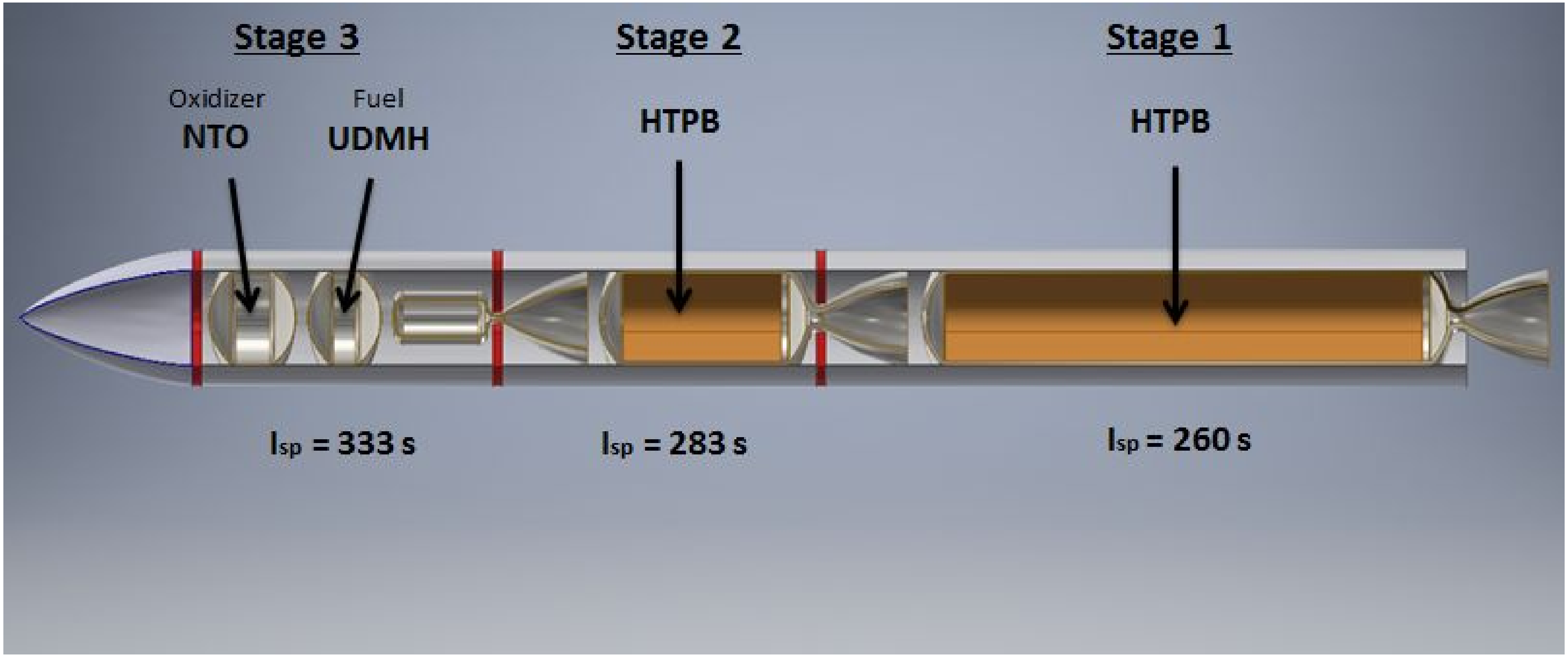
Pre Launch

Aiming for expedited launch procedure:

- Payload integration facility at each launch location
- Rolling maintenance checks for risk mitigation, reducing pre-flight check time
- Automating the following:
  - Facility operations
  - Clearing pad
  - Launch vehicle and payload system checks

Launch Staging Overview

3-Stage Rocket Model



Slide 119: Liquid Propellent Trade

Launch

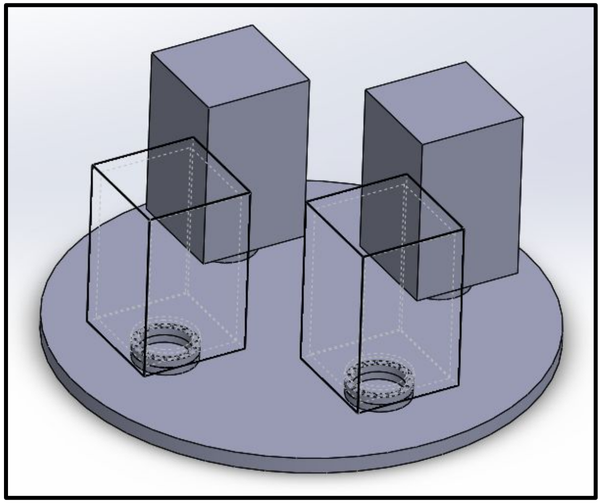
- *Goal: minimize ejection velocities*
  - *Rotational, positional, tumbling*

Trade	Status	Baselaine
Satellite Mounting: Axial vs Radial	Open	N/A
Deployment Direction	Open	Nadir/Zenith
Payload Release: Pyros vs Actuators	Open	Actuators
Payload Eject: Spring vs Thrusters	Open	Spring

Satellite Mounting Considerations

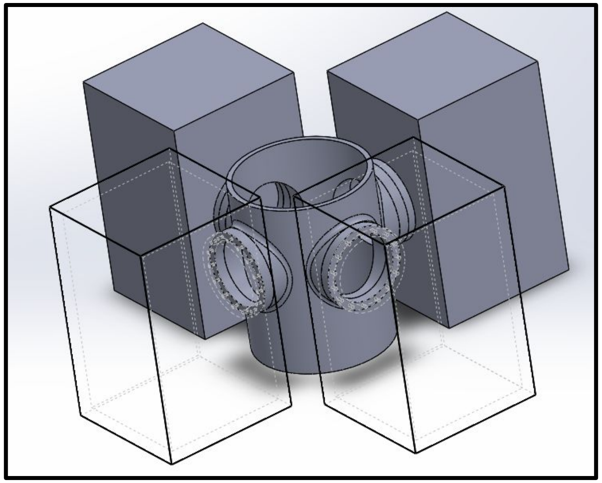
Axial

- Aligned with longitudinal forces
- Better for structural integrity
- Larger displacements due to loads



Radial

- Ability to deploy (2) sats quickly
- High stress areas near rings
- Less maneuvers for upper stage
- Additional structural mass added



Imaging Requirements Flowdown

Launch vehicle shall:

- have capability to reach a range of orbits with a worst case orbit of 567 X 3167 km
  - Worst case deltaV to re-circularize= 0.575 km/s
- have capability to account for our worst case launch location
  - Worst case deltaV based on launch site= 0.067 km/s
- phase all imaging satellites

Altitude	Inclination	RAAN Spacing (between planes)	True Anomaly Spacing (from first to last sat)
554 or 567 ± TBD	90° or 97° ± TBD	0.8° - 1.2° (depending on lat. of target)	6.5° ± TBD

Launch

Imaging Launch

- 2 payload configurations for imaging launches are being considered
  - 2 satellites per vehicle VS 4 satellites per vehicle
- Configuration scheme greatly affects:
  - Number of launch vehicles
  - Vehicle commonality
  - Stage and total vehicle masses
  - Time for all satellites to reach target orbits

Imaging Launch - 9.5 kg per satellite

2 Sats Per Vehicle

- 12 total vehicles
- Payload mass = 25.7 kg
  - Accounting for:
    - Adapter= 15% of payload mass
    - Fairing= 20% of payload mass
- Does not require RAAN change
- Increases vehicle commonality
- Potential to extend timeline

4 Sats Per Vehicle

- 6 total vehicles
- Payload mass = 51.3 kg
  - Accounting for:
    - Adapter= 15% of payload mass
    - Fairing= 20% of payload mass
- Requires on orbit RAAN change
- Decreases vehicle commonality

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Communications Requirements Flowdown

- Launch vehicle shall be capable of
  - reaching an elliptical orbit with perigee at 625 km and apogee at 918 km
  - variable ΔV for the purpose of latitude matching

Altitude	Inclination	True Anomaly Spacing (Between Satellites)
625 ± 7 km	Latitude ± 0.1°	40°± 6°

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Communications Launch

- Vehicle will launch directly into elliptical phasing orbits
  - 625 x 918 km injection orbit
  - Individual satellites burn to circularize at perigee
- 4 Satellites per Launch Vehicle
  - 7.5 kg per satellite
  - Total mass to orbit: **40.5 kg**
    - Accounting for:
      - Adapter= 15% of payload mass
      - Fairing= 20% of payload mass
- Variable performance upper stage required for latitude matching
- 4 Total Comms launches

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Launch Configuration

Mass Breakdown

	Comms	Imaging: 2 per LV	Imaging: 4 per LV
Total Payload (kg)	40.5	25.65	51.3
Stage 3 (kg)	269	208	417
Stage 2 (kg)	728	591	1,182
Stage 1 (kg)	2,655	2,262	4,525
Totals (kg)	**3,693**	**3,088**	**6,176**

ΔV Breakdown

***Payload Mass Includes Payload Adapter and Fairing**

***Assuming 0.1 mass fraction per stage**

Launch

Moving Forward

- Closing payload configuration study
- Closing upper stage propellant study
- Currently acquiring loading and trajectory program (ASTOS-AeroSpace Trajectory Optimization Software)
- Vibration and acoustic analysis tools
- Sizing and configuration of members and components
- Finalization of launch location/launch pad distribution
- Fairing design

Mission Conclusion

- System wrap up
  - 40 Satellites
    - 24 imaging satellites
    - 16 communications satellites
  - 4 launch sites
  - 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

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**

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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**

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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**

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**

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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**

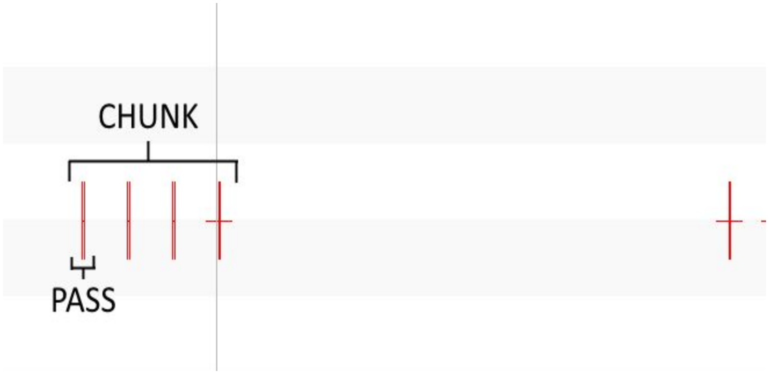
Correcting Orbits Vs. Non-Correcting Orbits - IMAGING

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 Specific Trades

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 - OPEN

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

Propulsion Method Trade - OPEN

Possible Engines

Make / Model	Drive Type	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)
Aerojet: MR-103	Mono	Hydrazine	0.33	1	2000	224	13.7	0.0049	0.0005
Aerojet: MR-111	Mono	Hydrazine	0.33	5.3	2208	229	13.6	0.024	0.0024
TRW: MRE-4	Mono	Hydrazine	0.5	9.8	2134	217	30	0.045	0.0046
Aerojet: MR-106	Mono	Hydrazine	0.52	30.7	2362	235	49.15	0.13	0.013
Aerojet: R-1E	BiProp	MMH/ NTO	2	111	2775	280	36	0.39	0.04
Vacco: Cold Gas x8	Mono	Hybrid Green (R134a)	0.1	0.002	392.4	40	5	0.00005	0.0000051
Busek: BGT X5	Mono	Green (AF-M315E)	1.5	0.5	2159	220	20	0.0023	0.00023
Busek: BGT5	Mono	Green (AF-M315E)	2	5	2256	230	50	0.022	0.0026
SSC: 1 N HPGP	Mono	LMP-103s	0.34	1	2305.522914	235	8	0.004255319149	
SSC: 5 N HPGP	Mono	LMP-103s	0.36	5	12262.5	250	10	0.02	
Aerojet MPS 130	**Mono**	**AF-M315E**	**2.2**	**1.5**	**2354.4**	**240**	**7**	**0.00625**	**0.000637**

Comms Mass-Power-Thermal w/o Prop

Subsystem	Components	Mass (kg)	Thermal Output (W)	Power Req'd (W)	POWER DUTY CYCLE (%)	SUBSYSTEM EFFICIENCY (%)
ADCS	Mags	0.5	0.48	2	40	40
	Attitude Sensor	0.1	0.5	1	100	50
Structure	Frame/ Harnessing (~30% of total mass)	1.38	0.3			
	Drag Sail (TBD)	0.5	0.001	0.5	1	80
Thermal	Heater	0.01	0.33	1	33	0
Comms Payload	Antenna	0.1	0.025	0	5	50
	Amplifier/ filter	0.5	2.5	13.5	5	50
	Transponder(s)	0.085	0			
CD&H	Computer	0.05	0.0025	0.5	5	90
Power Units	Batteries (Lithium example)	0.215	0.5			
	Solar Panels (Cells + Structure)	0.2				
Totals		**~ 5**	**~ 2**	**Avg: ~3 Max: ~20**		

Back: Communications Constellation

Comms Mass-Power-Thermal

Subystem	Components		Mass (kg)	Thermal Output (W)	Power Req'd (W)	POWER DUTY CYCLE (%)	SUBSYSTEM EFFICIENCY (%)
	TYPE	NAME					
ADCS	ACS Package **(WITH PROP)**	***BUILT IN WITH MPS-130 THRUSTER***					
	ACS Package **(WITHOUT PROP)**	Magtorquer - MT01 Compact Magtorquer	0.5	1	2	10	50
	Attitude Sensor **(WITH PROP)**	NSS Magnetometer ***AND*** NSS Cubesat Sun Sensor	0.205	0.00035	0.007	100	95
	Attitude Sensor **(WITHOUT PROP)**		0.205	0.00035	0.007	100	95
Propulsion	Engine	Aerojet MPS-130 Monoprop	2.2	21	30	2	30
	Propellant (phasing ~126)	Green Prop	0.54				
	Propellant (deorbit ~68)		0.28				
	Tank, valves, etc.		0.4				
Structure	Frame/ Harnessing (~30% of total mass) **(WITH PROP)**		2.1702	0.3			
	Frame/ Harnessing (~30% of total mass) **(WITHOUT PROP)**		1.2462	0.3			
	Drag Sail **(WITHOUT PROP) (x4)**	CanX-7	1.2	0.004	2	1	80
Thermal	Heater	Random Resistor	0.01	1	1	33	0
Comms Payload	Antenna	Patch with Quad Whips	0.1	0	0	5	50
	Transceiver(s) **(x15)**		1.275	6.75	13.5	5	50
CD&H	Computer		0.05	0.05	0.5	5	90
Power Units	Batteries **(WITH PROP)**	Li-Ion	0.39	0.5			
	Batteries **(WITHOUT PROP)**		0.23	0.5			
	Solar Arrays **(WITH PROP)**	Galium Arsenide	0.1				
	Solar Arrays **(WITHOUT PROP)**		0.1				
	PDU	10W Power Bundle (PDU+Battery)	0.242	0.75	3	100	75
GPS	Antenna	Tuna Can	0.082	0	0	95	80
	Receiver		0.16	0.2	1	95	80
TOTALS (With Prop)			**MASS:**	**AVG THERMAL OUTPUT :**	**AVG POWER:**	**MAX POWER REQ'D:**	**MAX THERMAL OUTPUT :**
			8.2042	30.55035	5.587	35.507	30.55035
TOTALS (Without Prop)			**MASS:**	**AVG THERMAL OUTPUT :**	**AVG POWER:**	**MAX POWER REQ'D:**	**MAX THERMAL OUTPUT :**
			5.4002	10.55435	5.207	21.007	

Back: Communications Constellation

Comms Component List

Subsystem	Components	Dimensions (m x m x m)			Volume (cubic cm)
		X	Y	Z	
ADCS	Magnetorquer	0.1	0.095	0.017	161.5
	Attitude Sensor	0.05	0.019	0.002	1.9
GPS	Receiver	0.09398	0.05588	0.02604	136.7517265
	Antenna	0.0528	0.0528	0.0175	48.7872
Structure	Frame/ Harnessing (~30% of total mass)				NA
	Drag Sail/ Deployer (Non-Deployed) (TRIANGLE)	0.09	0.09	0.04	324
Thermal	Heater (TBD				Negligible
	Radiator (TBD)				NA
Comms Payload	Antenna	0.05	0.05	0.002	5
	Transponder/ Transeiver (1 channel)	0.096	0.09	0.1	864
CD&H	Computer	0.096	0.09	0.012	103.68
Power Units	Batteries (Lithium example)	0.1	0.1	0.05	500
	Solar Panels (Cells + Structure)	0.066	0.066	0.005	21.78
	PDU	0.095	0.09	0.0175	149.625

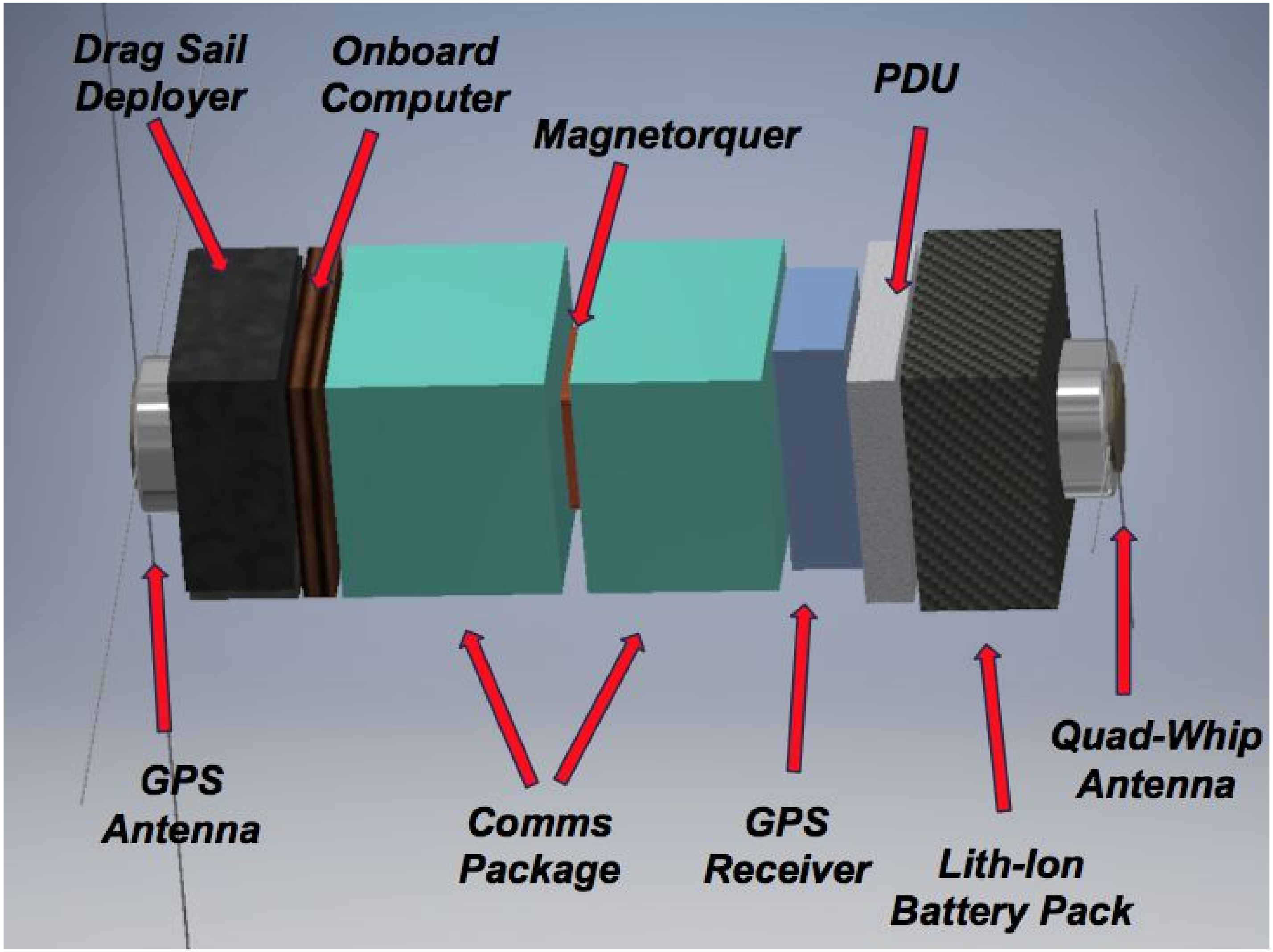
Back: Communications Constellation

Communications Constellation

Components

- Comms Payload: 15 solid state UHF/VHF radios
- Antennas: 2 sets of 4 whips in phase quadrature (one for UHF and one for VHF)
- Propulsion: Aerojet MPS-130
- ADCS:
  - Determination Sensor: TBD
  - Thrusting: Aerojet MPS-130 integrated ACS package
  - 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

Configuration w/o Prop



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

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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

	Vusek Thrusters (12)	Reaction Wheels (4) and Magnetometer (1)
Power, Watts	20	1.5
Mass, Kg	6	0.35
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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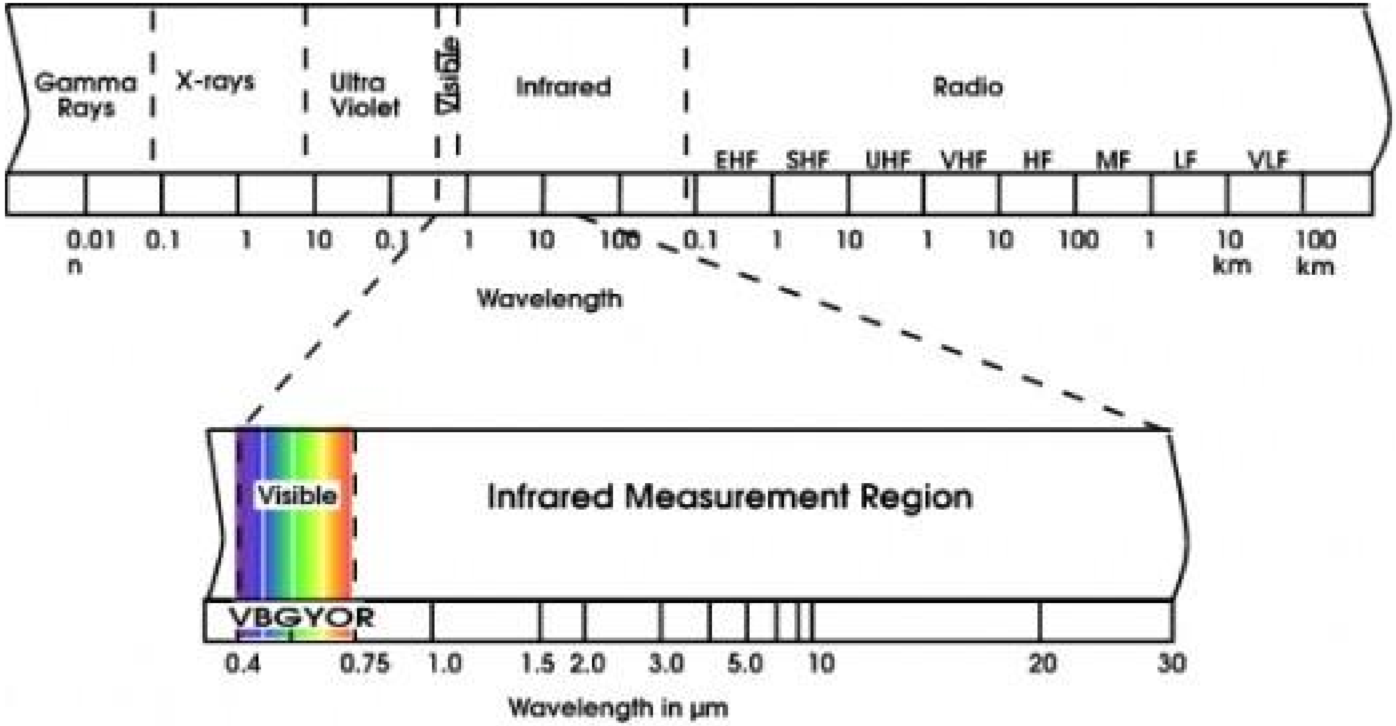
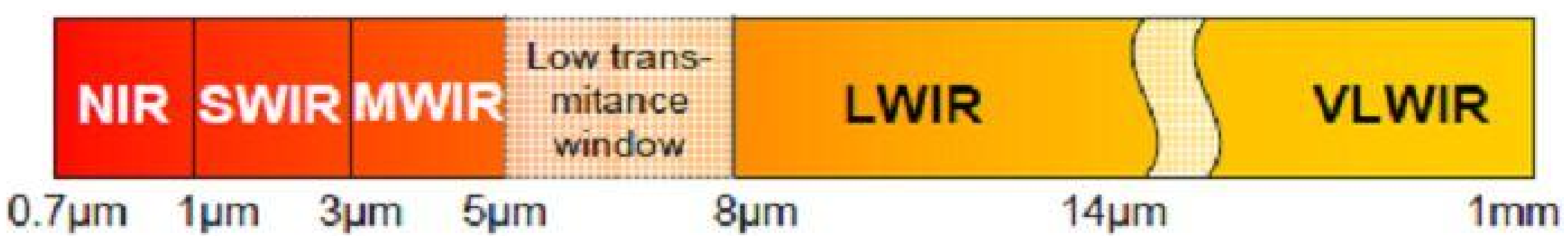
Spectral Wavelengths





Power Subsystem

- **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%	Unsure
Battery Energy Density	145 Whr/Kg	Reasonable (eg. Li-Ion)
Battery Max. Depth of Discharge	40%	Reasonable

Power Budget

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Imaging Satellite

Component	Temperature Range (K)
Reaction Wheels	233 to 358
Magnetorquers	238 to 348
Attitude Sensor	233 to 353
Position Sensor	263 to 323
Propellant	263 to 323
Tank/Valves for Propellant	244 to 344
Structure Frame	078 to 366
Optics	263 to 323
Comms Equipment	233 to 353
CD&H Amplifiers	228 to 358
CD&H Computer	218 to 398
Batteries	273 to 318
Solar Panels	173 to 398

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**	

Back: Launch Sites

LV Baseline

<u>What our **Closed** Trades Determined</u>

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

<u>What our **Open** Trades Determined... So far</u>

- 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

<u>Decision: Build</u>

- 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

Pre-Launch Timeline

T-6 hours	Launch Provider Informed of Disaster	
	Personnel Called Out to Launch Site	
T-4.5 hours	Pad Prep Begins	Personnel given 90 min to commute
	Satellite Prep Begins	Payload processing will be mostly complete, only minimal work done right before launch: battery installation, propellant loading, etc. Satellite could possibly already be on adapter, depending on design
	LV Prep Begins	Flight termination system installation, remove before flight items, etc. Vehicle could possibly already be mated to the strongback, depending on launch design.
T-2.5 hours	Satellite Prep Ends	Satellite given 2 hours to prep
	LV Prep Ends	LV given 2 hours to prep, fts usually given a full day, hence why it is given the most amount of time.
	LV Vertical	Accounting for 30 min to get LV vertical on pad
	Pad Clear	Accounting for 1 hour to clear pad and start checks
	LV Checks Begin	
T-1 hour	LV Prop Load Begins	1 hour given to load prop
T-0	Launch	

Back: Pre-Launch Timeline

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 was selected for baseline tests due to performance parameters
- 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

Liquid Propellant Trade

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

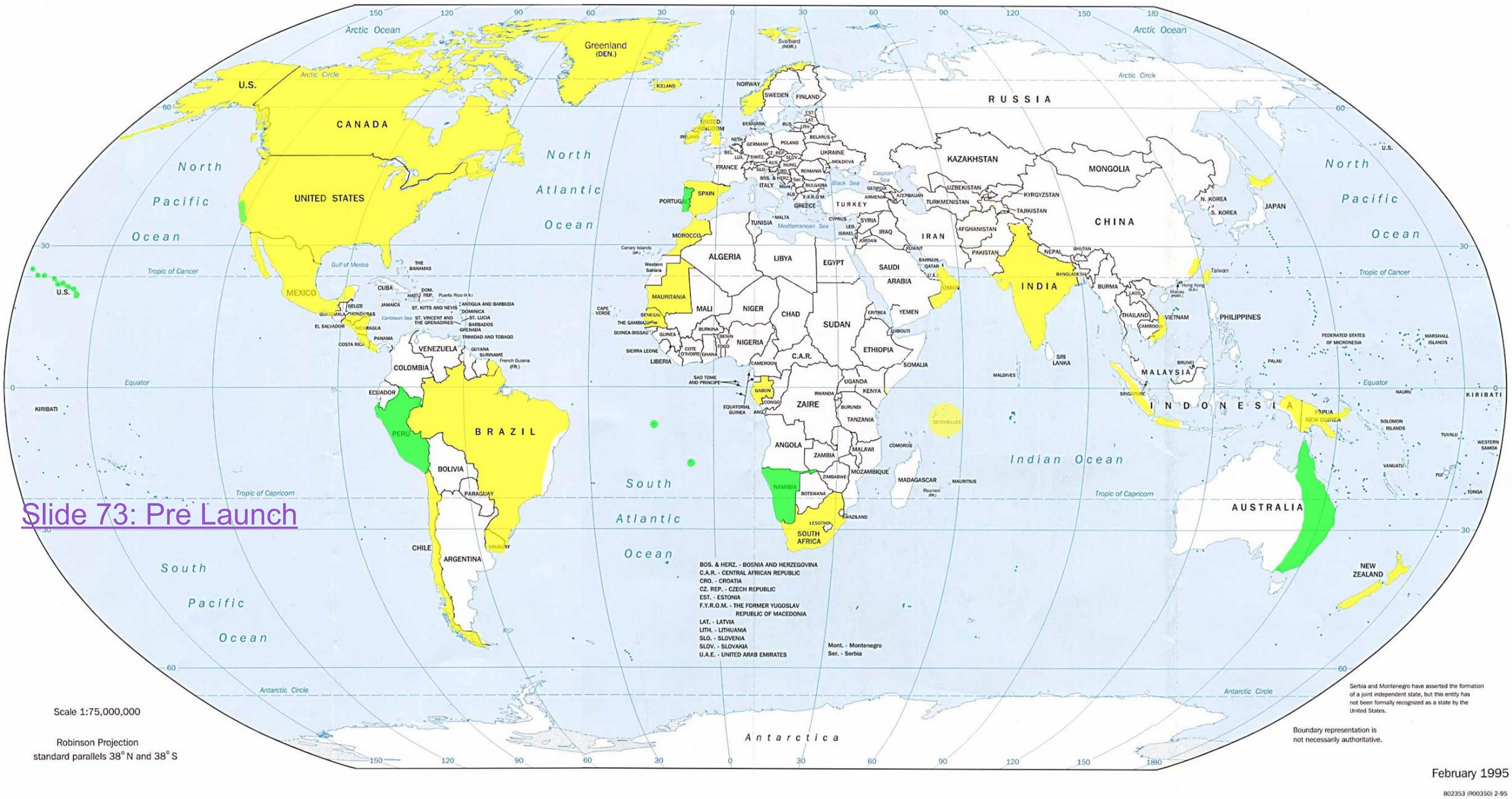
- Mission Cost calculated for mass of satellite prop

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

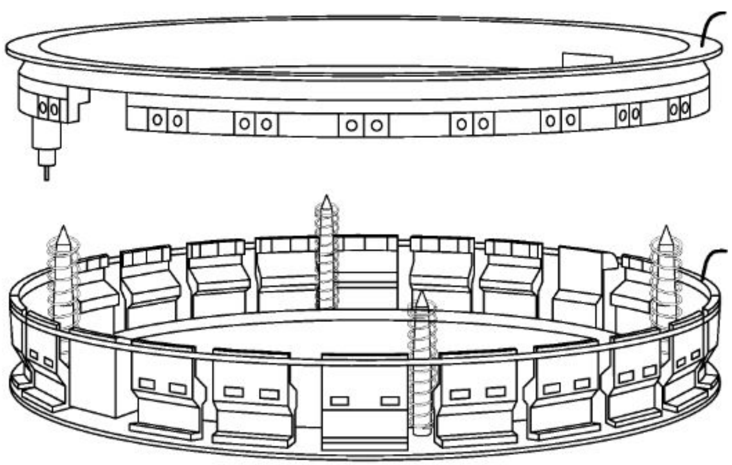


Slide 73: Pre Launch

Launch

Payload

- Satellites want to minimize ejection velocities
  - Rotational, positional, tumbling
- Direction of deployment consideration
  - Affects sat configuration on LV
  - Ideal to deploy nadir or zenith
- Pyros vs actuators for release mechanism
  - Actuators produce no shock but require more power
- Spring system vs thrusters for ejection
  - Researching lightband separation system



Launch Configuration

- **ΔV Breakdown (km/s)**

	Comms	Imaging: 2 per LV	Imaging: 4 per LV
Payload Mass (kg)	40.5	25.6	51.3
Stage 3	6.12	6.85	6.85
Stage 2	2.40	2.57	2.57
Stage 1	2.40	2.57	2.57
Totals	**10.97**	**11.99**	**11.99**

Mass Breakdown

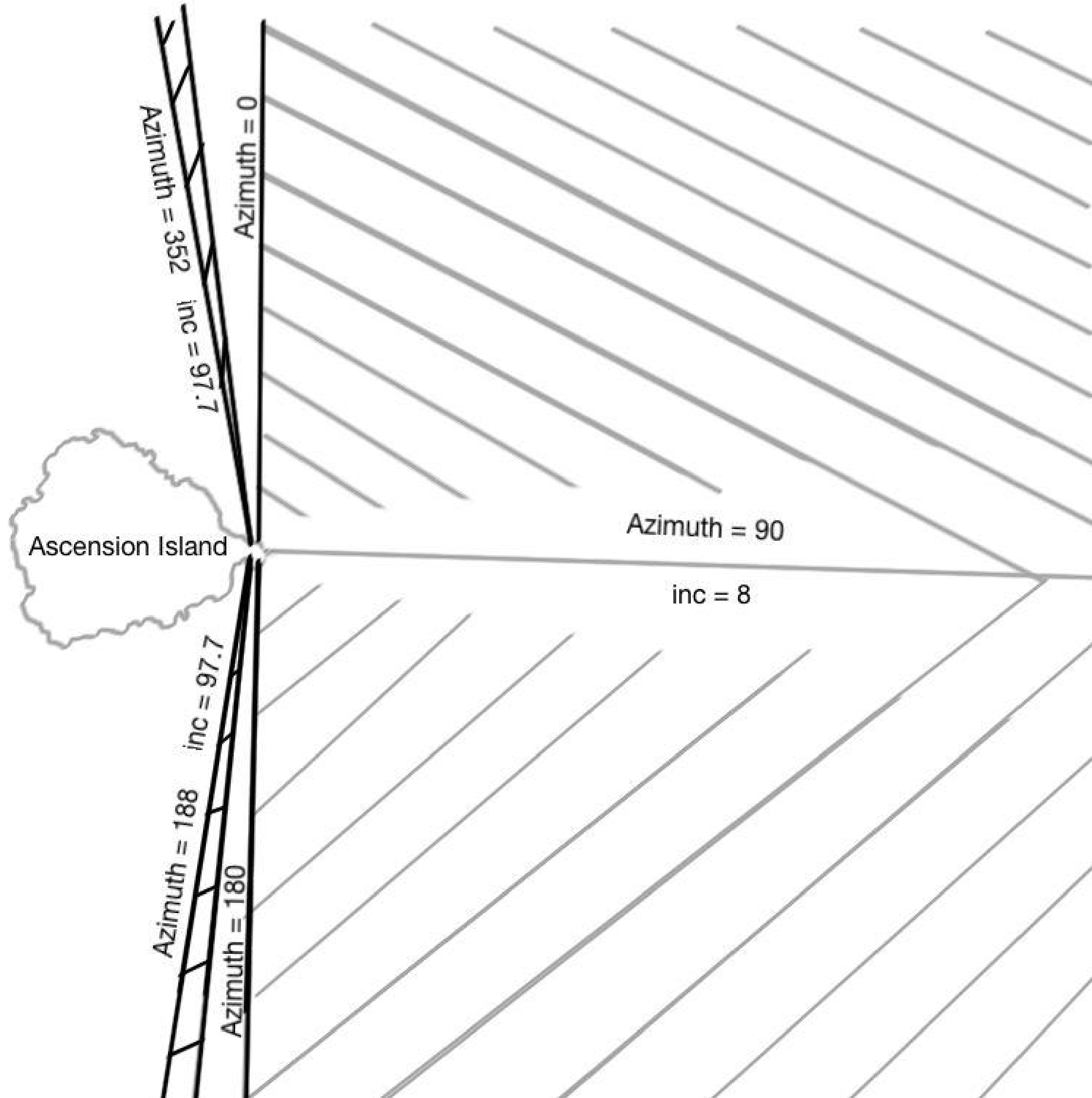
***Assuming 0.1 mass fraction per stage**

Hawaii Launch Range

[Return to Launch Pad Distribution Slide]

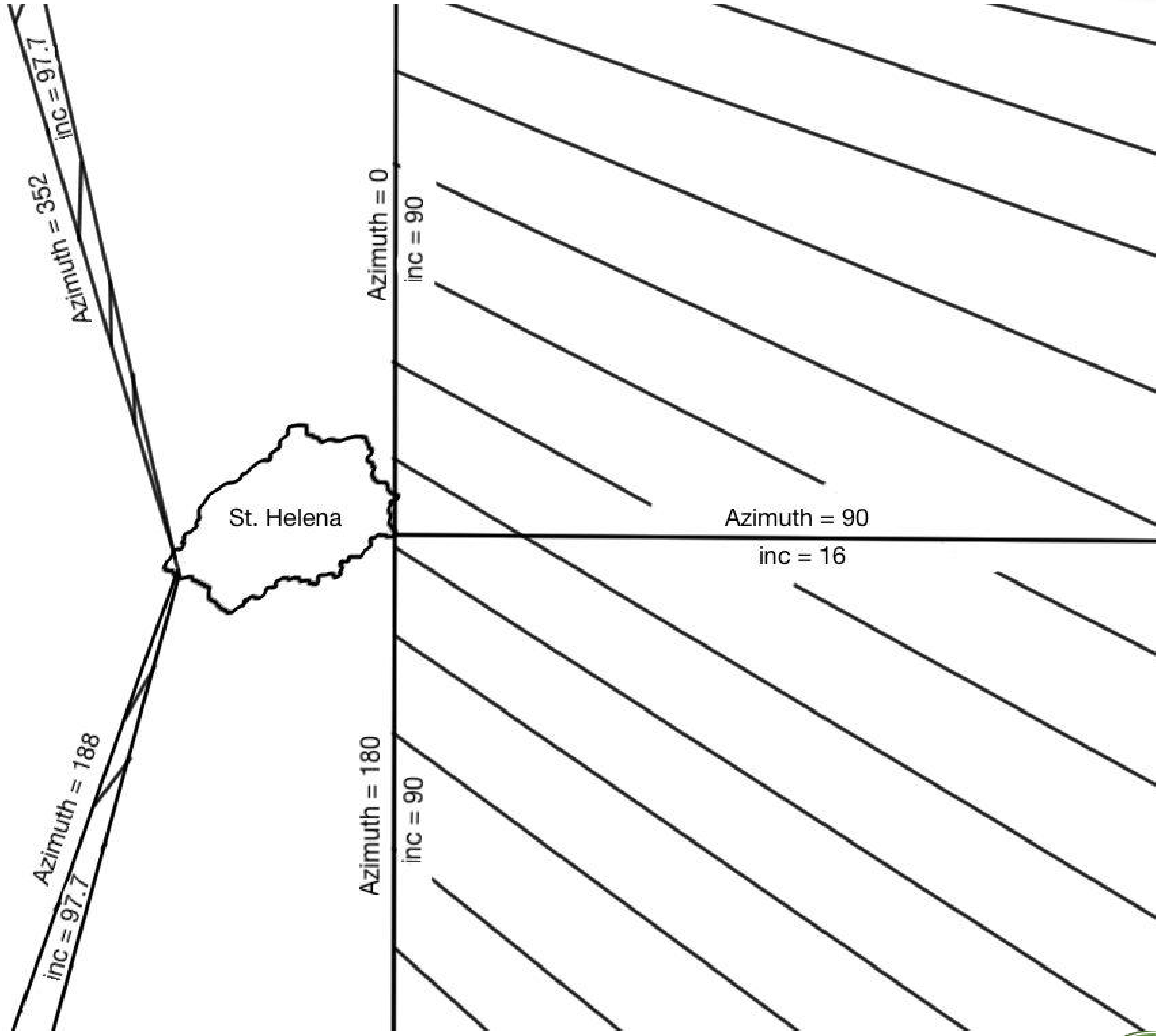
Ascension Launch Range

CAL POLY
SAN LUIS OBISPO



[Return to Launch Pad Distribution Slide]

St. Helena Launch Range



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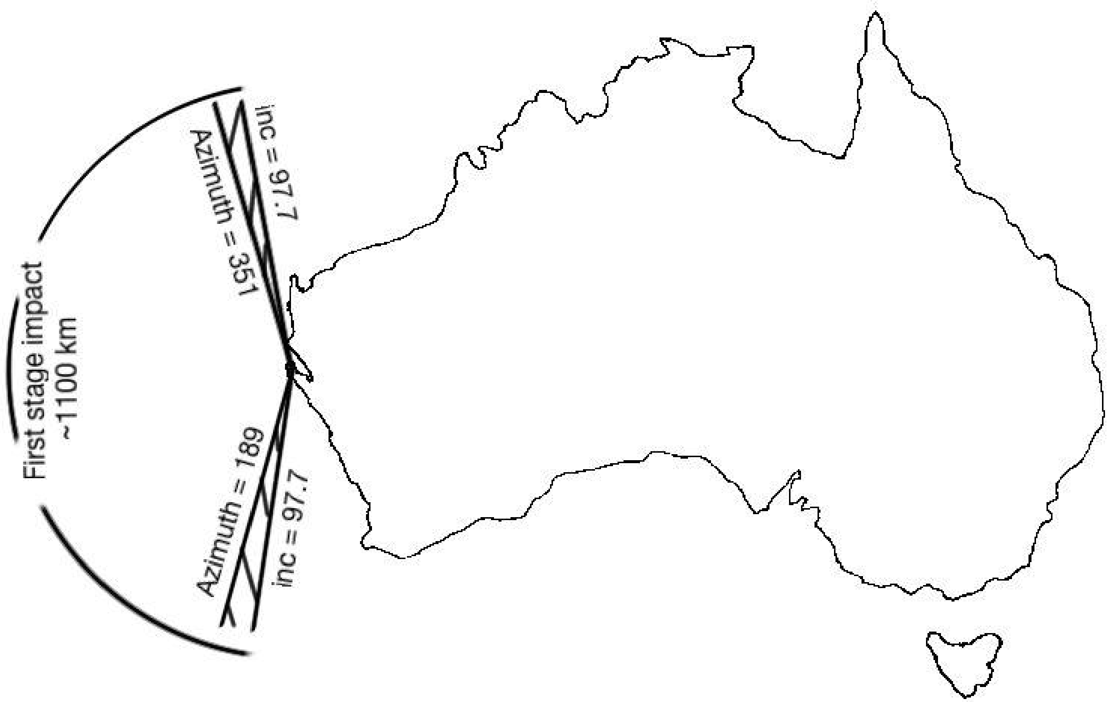
Australia Launch Range



[Return to Launch Pad Distribution Slide]