A Need For Speed: Tips for Fielding Responsive Space Systems

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Space Power Workshop
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Introduction

Currently: Deputy Program Manager, Tactical Space Systems, MIT Lincoln Lab

- Developing payloads for civil and defense applications
- Expertise in rapid COTS qualification for space
- Assisting Space Systems Integration Office at SSC

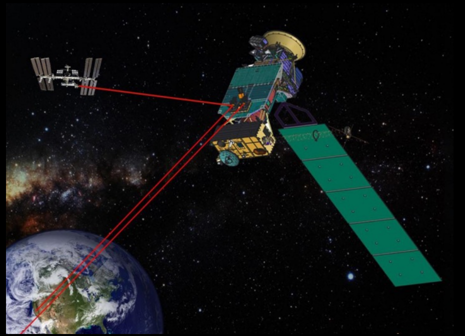
Public missions I've worked on at MITLL:

- LEMNOS optical comms payload
- Agile MicroSat (6U CubeSat)
- Stem Cell Scaffolding

Previously:

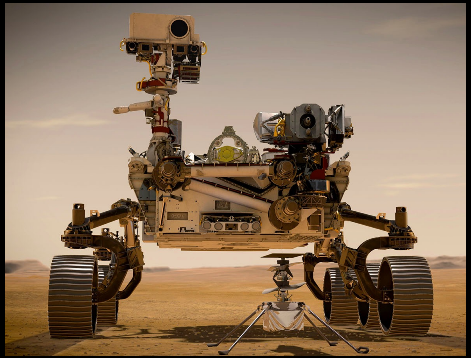
- Solar array engineer, SpaceX Starlink mega-constellation

Agile MicroSat
Image Credit: Blue Canyon Technologies



LEMNOS Optical Communication Payload
Image Credit: MIT LL

Stack of Starlink satellites
Image Credit: SpaceX



Mars2020 rover
Image Credit: Jet Propulsion Laboratory

Discussion Roadmap

1. Responsive space – what is it, and why now?

2. Streamlining program lifecycles
   – Concept
   – Design
   – Test
   – Launch
   – Next Gen

3. Broader applications

Old Priority with New Urgency: "Responsive Space"

THE WHITE HOUSE

WASHINGTON

December 21, 2004

NATIONAL SECURITY PRESIDENTIAL DIRECTIVE/NSPD-40

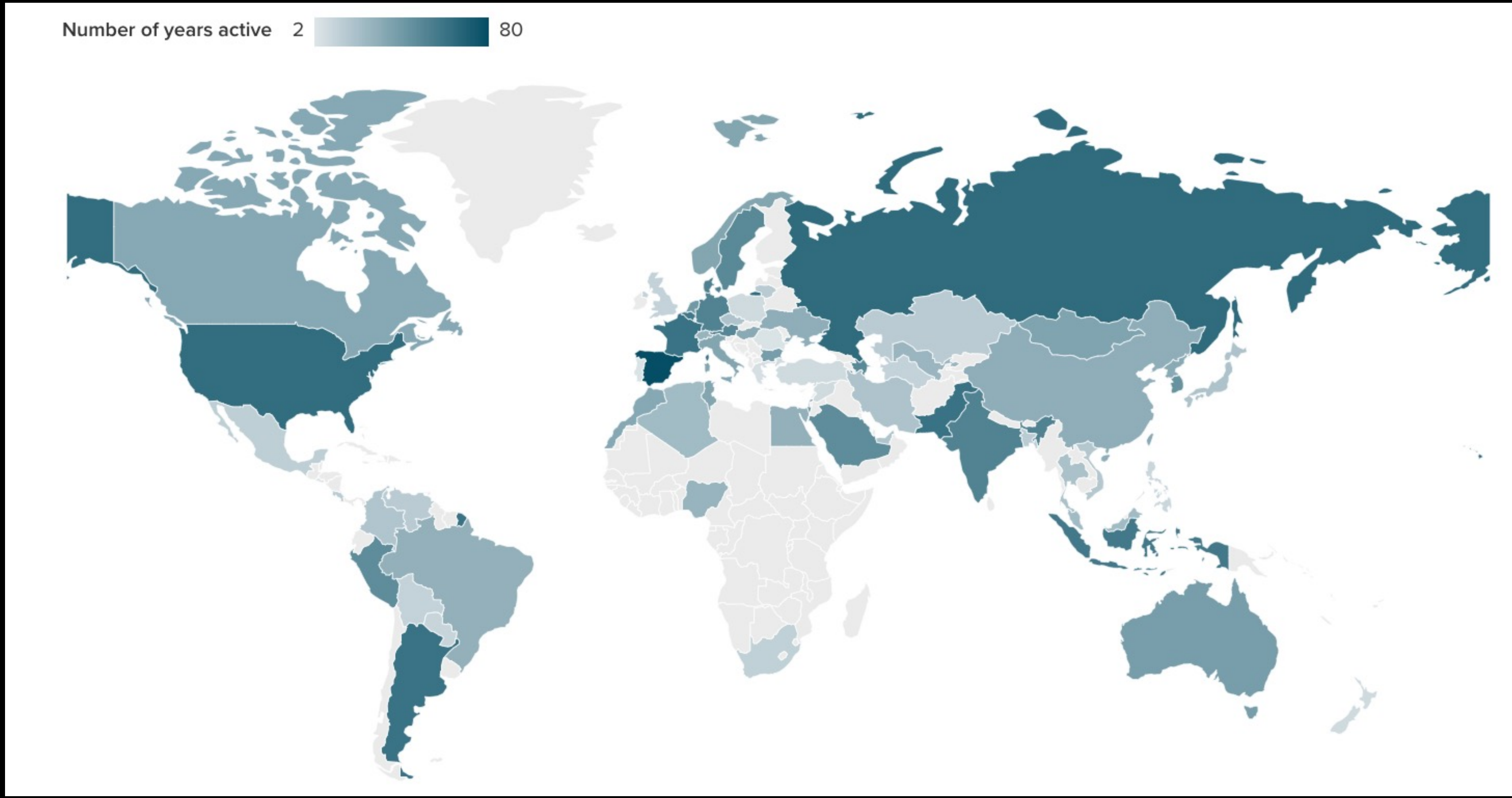
MEMORANDUM FOR THE VICE PRESIDENT
THE SECRETARY OF STATE
THE SECRETARY OF THE TREASURY
THE SECRETARY OF DEFENSE
THE ATTORNEY GENERAL
THE SECRETARY OF COMMERCE
THE SECRETARY OF TRANSPORTATION
THE SECRETARY OF ENERGY
THE SECRETARY OF HOMELAND SECURITY
CHIEF OF STAFF TO THE PRESIDENT
DIRECTOR, OFFICE OF MANAGEMENT AND BUDGET
ASSISTANT TO THE PRESIDENT FOR NATIONAL SECURITY AFFAIRS
ASSISTANT TO THE PRESIDENT FOR ECONOMIC POLICY
ASSISTANT TO THE PRESIDENT FOR DOMESTIC POLICY
ASSISTANT TO THE PRESIDENT FOR HOMELAND SECURITY
DIRECTOR, OFFICE OF SCIENCE AND TECHNOLOGY POLICY
UNITED STATES TRADE REPRESENTATIVE
DIRECTOR OF CENTRAL INTELLIGENCE
CHAIRMAN OF THE JOINT CHIEFS OF STAFF
ADMINISTRATOR, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
DIRECTOR, NATIONAL SCIENCE FOUNDATION

SUBJECT: U.S. Space Transportation Policy

Demonstrate an initial capability for operationally responsive access to and use of space – providing capacity to respond to unexpected loss or degradation of selected capabilities, and/or to provide timely availability of tailored or new capabilities – to support national security requirements

Why Now?

70+ countries with own space agencies
4 countries with demonstrated anti-satellite capabilities (US, China, Russia, India)



World map of countries with active space agencies

Credit: “The Future of Security in Space: A Thirty-Year US Strategy.” Atlantic Council, Feb 2021

SCIENCE NEWS

China's new moon mission returns the first lunar samples since 1976

Credit: National Geographic, Nov 2020

NEWS | 09 February 2021

Elation as first Arab Mars mission reaches orbit

UAE’s Hope spacecraft is poised to make pioneering measurements of the Martian atmosphere.

By Elizabeth Gibney

Credit: Nature, Feb 2021

ISRO launched 177 foreign satellites from 19 nations in 5 years, House told

By HT Correspondent

Credit: Hindustan Times, Dec 2022

Why Now?

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4 countries with demonstrated anti-satellite capabilities (US, China, Russia, India)

Ever-growing dependency on space assets for key capabilities:

- Detection, tracking & targeting
- Environmental monitoring
- Space situational awareness
- Precise navigation & timing
- Secure communication
- Etc.

How Fast is Fast Enough?

Recent example: Starlink reestablishing Internet in Ukraine

Mykhailo Fedorov @FedorovMykhailo · Feb 26
Ukraine government official

@elonmusk, while you try to colonize Mars — Russia try to occupy Ukraine! While your rockets successfully land from space — Russian rockets attack Ukrainian civil people! We ask you to provide Ukraine with Starlink stations and to address sane Russians to stand.

3,133 25.4K 178.2K

Elon Musk
@elonmusk

Replying to @FedorovMykhailo

Starlink service is now active in Ukraine. More terminals en route.

5:33 PM · Feb 26, 2022 · Twitter for iPhone

Exchange between Mykhailo Federov and Elon Musk
Credit: Twitter, Feb 2022

Döpfner: What happens if the Russians and Chinese are targeting satellites? Is that also a threat for Starlink?

Musk: It was interesting to view the Russian anti-satellite demonstration a few months ago in the context of this conflict. Because that caused a lot of strife for satellite operators. It even had some danger for the space station, where there are Russian cosmonauts. So why did they do that? It was a message in advance of the Ukraine invasion. If you attempt to take out Starlink, this is not easy because there are 2000 satellites. That means a lot of anti-satellite missiles. I hope we do not have to put this to a test, but I think we can launch satellites faster than they can launch anti-satellites missiles.

Elon Musk interview
Credit: Business Insider interview, March 2022

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Elon Musk interview
Credit: Business Insider interview, March 2022

Question: can we replenish key space capabilities on relevant timescale?

Are We Hitting the Mark?

Systematic cost and schedule overruns in large acquisitions point to room for improvement

Program	Total program cost ($bil) and % change from first full estimate to current estimate	QTY	Schedule change (months)
Advanced Extremely High Frequency (AEHF) Protected satellite communications	**$16.1** **116%**	original: 5 current: 6	44
Enhanced Polar System-Recapitalization (EPS-R) Protected satellite communications	**$1.2** **0%**	original: 2 current: 2	0
Global Positioning System (GPS) III Positioning, navigation and timing	**$6.0** **29%**	original: 8 current: 10	41
Global Positioning System Next Generation Operational Control System (GPS OCX) Command and control system for GPS III satellites	**$6.7** **73%**	original: 1 current: 1	58
National Security Space Launch (NSSL) Launch	**$65** **217%**	original: 181 current: 192	8
Space Based Infrared System (SBIRS) Missile warning, infrared intelligence, surveillance, and reconnaissance	**$20.7** **261%**	original: 5 current: 6	107
Space Fence Ground-Based Radar System Increment 1 Space object detection	**$1.6** **-8.3%**	original: 1 current: 1	8
Wideband Global SATCOM (WGS) Wideband satellite communications	**$5.0** **260%**	original: 3 current: 11	49

Credit: GAO analysis of Department of Defense (DOD) information. | GAO-21-520T

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Traditional Mission Architectures

Communications
Inmarsat-4A F4, Alphasat
Credit: ESA

Earth Imaging
Landsat-7
Credit: NASA

Weather Mapping
Suomi NPP
Credit: Ball Aerospace

Small Satellites Disrupting Traditional Mission Architectures

Communications
Inmarsat-4A F4, Alphasat
Credit: ESA

Weather mapping
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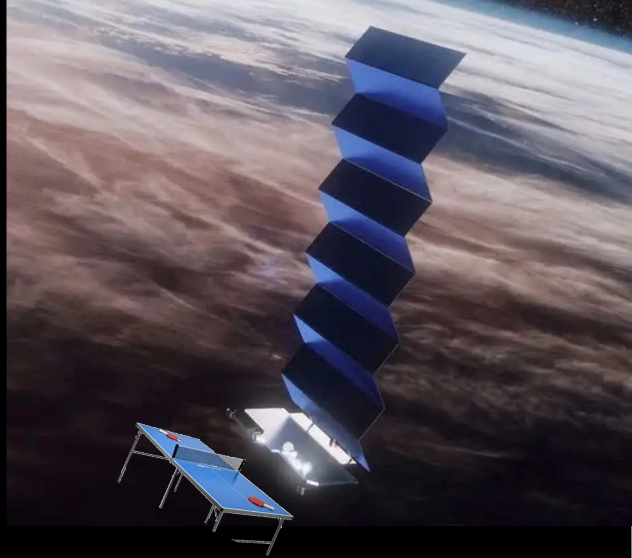
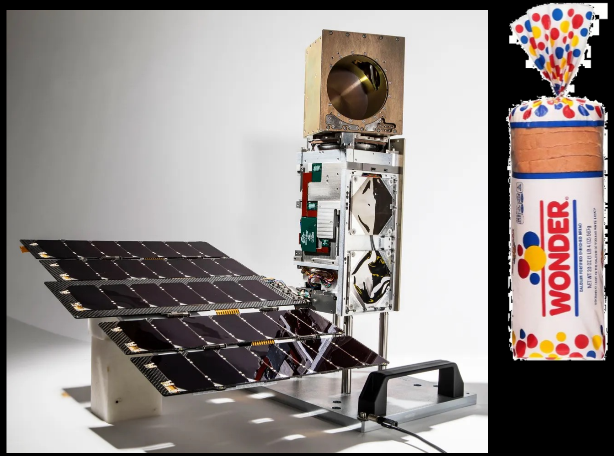
Earth imaging
Landsat-7
Credit: NASA

Earth imaging
Dove constellation
Credit: Planet Lab



Communications
Starlink constellation
Credit: SpaceX



Weather mapping
TROPICS constellation
Photo Credit: Blue Canyon Technologies

Strategic Considerations

	HVA Architecture	Small Satellites (CubeSats, Nanosatellites, etc.)
Size	1000s of kg	< 100s of kg
Cost/Sat	$500 million - $3+ billion	< 10s of millions
QTY	1-2 sats per gen	Large constellations possible
Dev. Time	5-10+ years	< 2-3 years, rapid iterations
Reliability And Risk	Strict requirements per vehicle *"Failure is not an option"*	Quantity as fault tolerance *"Learn fast"*
Security	Single points of failure	Resiliency through distribution
Capabilities	Exquisite instrument suites Large aperture	High revisit rates, distributed C2 Diverse configs

Example Mission

	NPP Suomi and JPSS	TROPICS
Size	2100-2600 kg[1]	< 10 kg
Cost/Sat	$12.9 billion (JPSS life-cycle)[2]	<1 million/sat
QTY	3 launched[3], 5 planned	5 launched, 20+ planned
Dev. Time	~10 years (for NPP Suomi)	< 2-3 years
Payload	5 instruments	1 instrument (radiometer)

Suomi NPP
Credit: NASA/GSFC

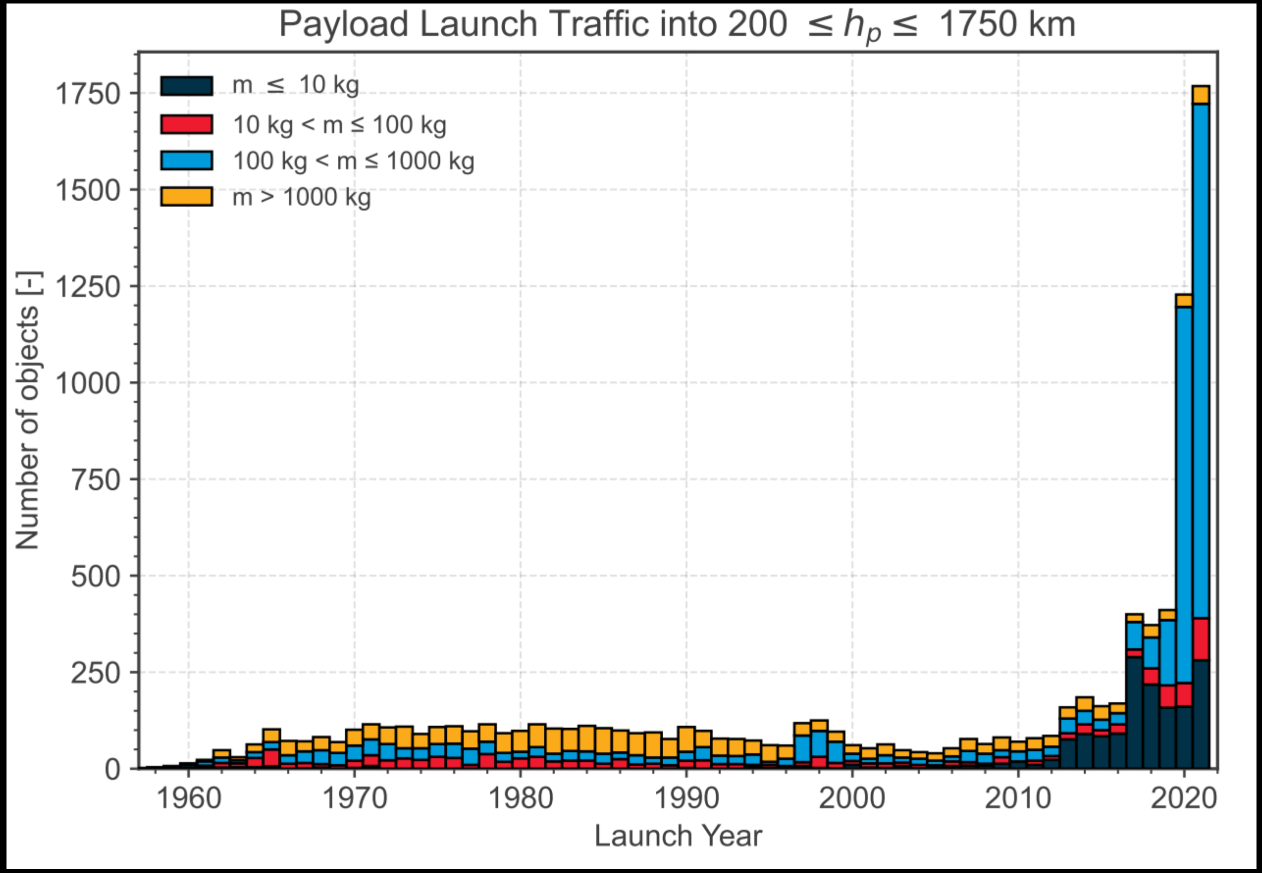
TROPICS CubeSat Fleet
Credit: Blue Canyon Technologies

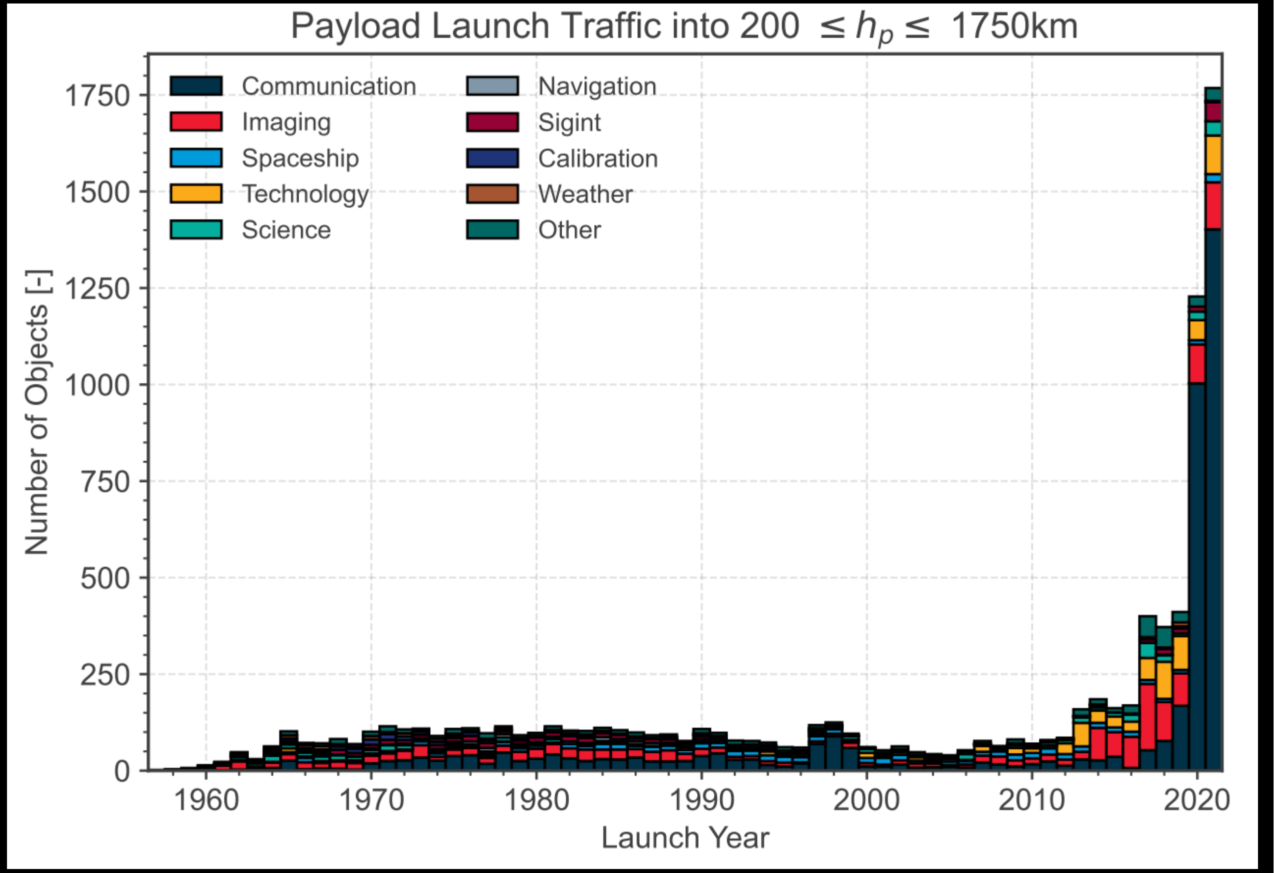
Credit: NASA

1) https://www.eoportal.org/satellite-missions/suomi-npp#suomi-npp-national-polar-orbiting-partnership-mission
2) https://spacenews.com/jpss-cost-estimate-rises-129b-through-2028/
3) https://www.nesdis.noaa.gov/our-satellites/currently-flying/joint-polar-satellite-system

Small Satellites Dominating Low Earth Orbit

Evolution of launch traffic in LEO per mission type (left) and mass category (right)





ESA's Annual Space Environment Report

Credit: ESA Space Debris Office, 22 April 2022

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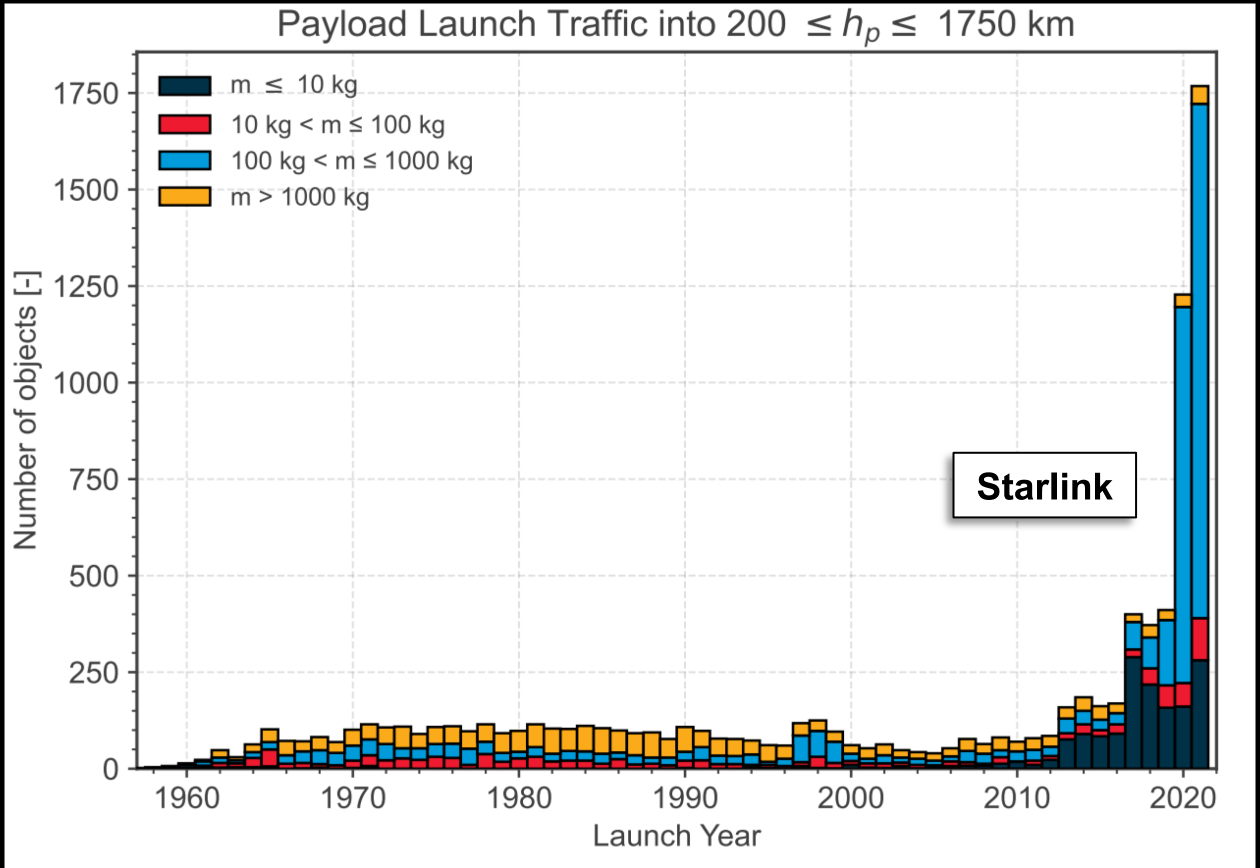

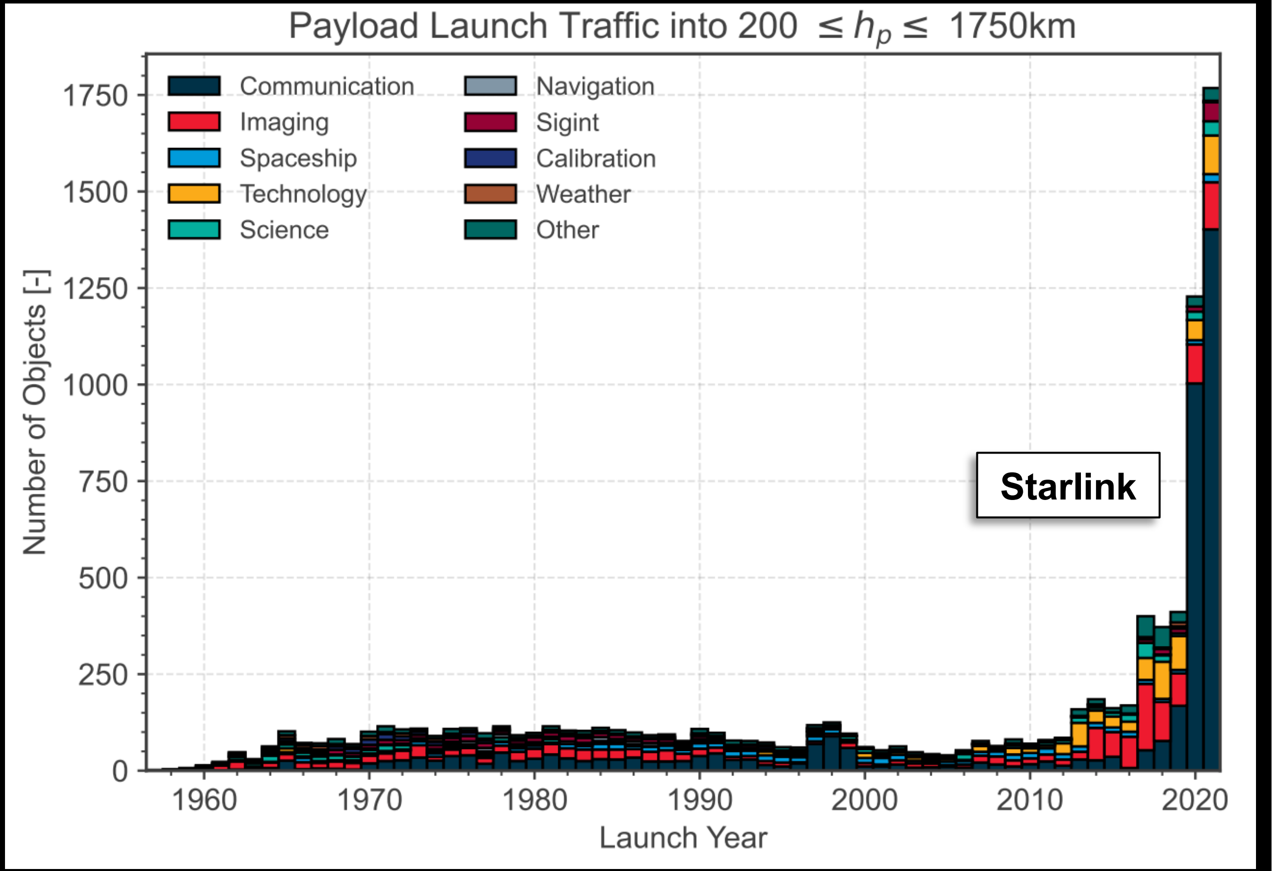

ESA's Annual Space Environment Report

Credit: ESA Space Debris Office, 22 April 2022

Starlink Overview

Goal	Global, low-latency via mega-constellation
Architecture	Proliferated LEO, 5400+ units launched (as of Feb ’24)[1]
Dev. Time	~1 year from Tintin launch (Feb 2018)[2] to first 60 Starlink satellites on-orbit (May 2019)[3]
Prod. Rate	120 satellites per month (as of July 2020)[4]
Launch	Rate: ~2/month Vehicle: Falcon 9 or (ultimately) Starship[5]

Question: what kind of architecture would these requirements incentivize?

1) https://spacenews.com/spacex-to-deorbit-100-older-starlink-satellites/
2) https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2018-020C
3) https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2019-074D#:~:text=Later%20sub%2Dconstellations%20are%20planned,size%20to%20nearly%2012000%20satellites.
4) https://www.cnbc.com/2020/08/10/spacex-starlink-satellte-production-now-120-per-month.html#
5) https://www.washingtonpost.com/technology/2024/03/14/spacex-starship-test-flight/

Restraint with Scoping & Requirements Enables Speed

New architectures incentivize requirement restraint that enables faster mission fielding

Observations from lived experience across several defense missions & industry…

Traditional Approach

- Limited launch pipeline incentivizes scope creep
  - Pressure to aggregate capabilities → coupled delays & cost
- Rigid reliability & sourcing requirements limits speed
  - Procurement → long lead, few vendors, $$
  - High qualification burden → slow tech infusion

Restraint with Scoping & Requirements Enables Speed

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Observations from lived experience across several defense missions & industry…

Traditional Approach	Alternative Approach
• Limited launch pipeline incentivizes scope creep - Pressure to aggregate capabilities → coupled delays & cost - Rigid reliability & sourcing requirements limits speed - Procurement → long lead, few vendors, $$ - High qualification burden → slow tech infusion	• Frequent launch opportunities restrains scope creep - Pressure to maintain schedule → capabilities & costs decoupled • Constellation redundancy reduces vehicle reqs, increases flexibility - Procurement → COTS options, short lead, $ - Lower qualification burden → faster infusion

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Some Helpful Design Principles

Rapid missions require reevaluating traditional design practices

Questioning “heritage”

- Evaluate areas of conservatism (ex. is rad hard necessary?)
- Reduce dependence on limited/$$ supply chains

Emphasizing simplicity

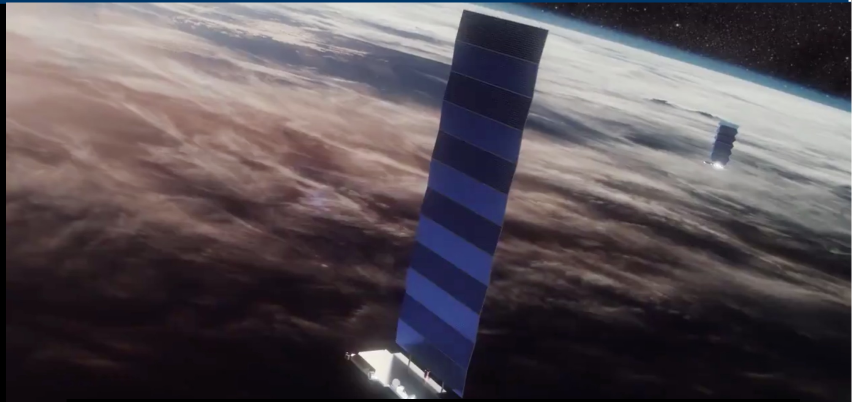
- COTS options? Terrestrial analogs?

Baselining iteration – not perfection

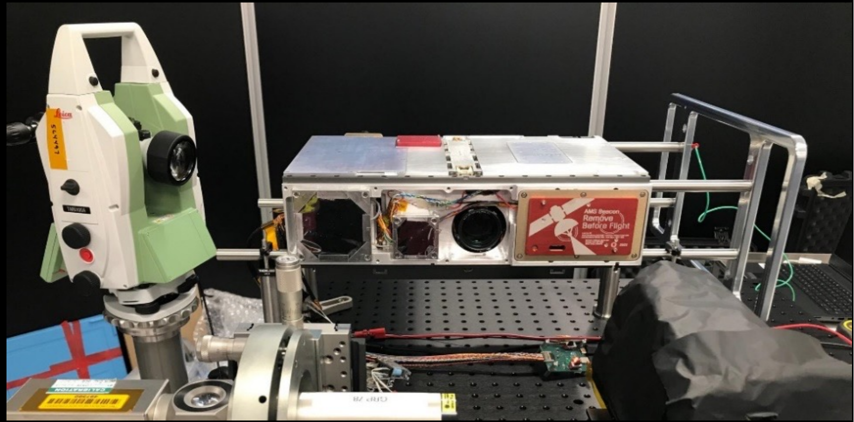
- Use low-cost vehicle/launch for iterative capability growth

Strategically limiting impact of on-orbit failures

- Accommodate anomalies in baseline
- Starlink satellites designed to passively deorbit due to atmospheric drag in case of failure[1]



Artist rendering of deployed Starlink array
Credit: SpaceX



Flight unit Agile MicroSat with ground equipment
Credit: MITLL

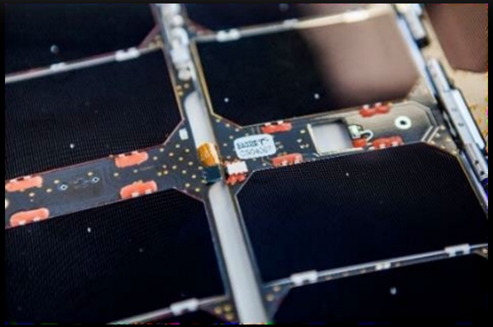
1) https://old.reddit.com/r/spacex/comments/gxb7j1/we_are_the_spacex_software_team_ask_us_anything/ft66thc/

COTS Enabling Small Satellites

Advances in miniaturization, standardization & reliability improving performance

Advanced Power Solutions

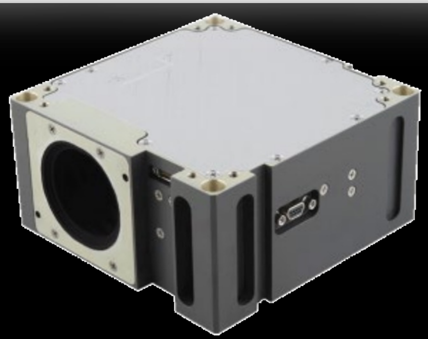
Credit: AAC Clyde Space



Ex. High efficiency, thin film, etc.

High-Precision Pointing and Navigation

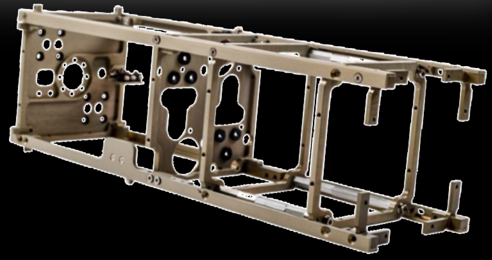
Credit: Blue Canyon Technologies



<0.1° pointing accuracy, high reliability

Standardized Buses

Credit: NanoAvionics



Mass produced low-cost structures, interchangeable payloads

Cheap Compute

Credit: Texas Instruments

Decreasing costs for rad-hard chips, higher performance

Small Propulsion

Credit: ENPULSION

Various small propulsion systems on-market (ion, cold gas, etc)

Ground Station as Service

Credit: ViaSat

For rent sat command, control & data downlink

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Reevaluating Role of Ground Test

What risk reduction would be prioritized if you only have months?

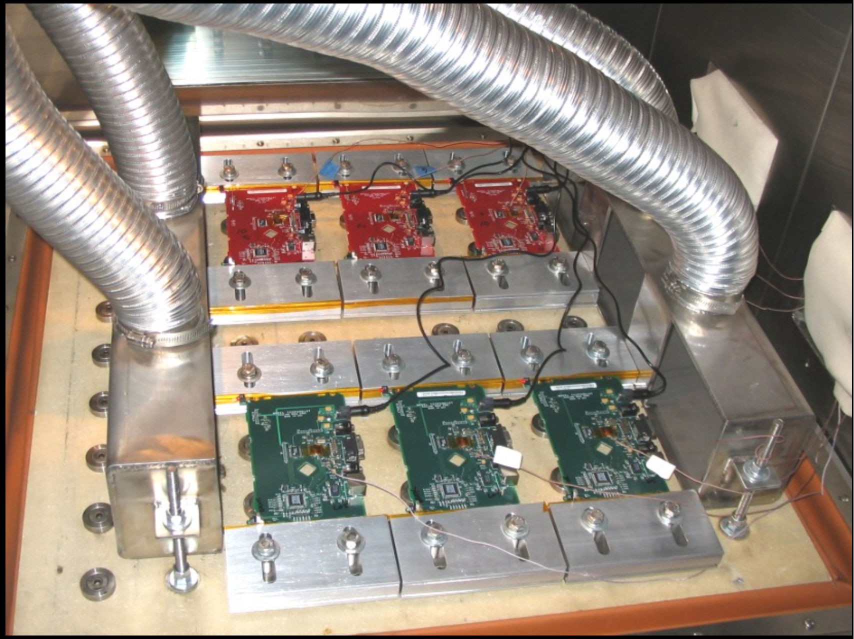
Prioritizing tests with highest value added

- Burn-down highest likelihood/criticality risks
- Demos
- Process development

Leveraging on-orbit vehicles for system qualification

- Test configurations in space in lieu of years of costly ground campaigns
- Consider diagnostics for improving understanding of system & anomalies

Learning lessons from high-volume industries



Printed circuit boards vetted with Highly Accelerated Life Testing
Credit: Delserro Engineering Solutions

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Criticality of Rapid Launch

Rapid and consistent launch can collapse feedback loop b/w design & test, quick upgrades

Ensuring continuous software and hardware upgrades

- Starlink did not have a launch in which the satellites going into the constellation hadn't changed from the last launch (as of May 2021)[1]

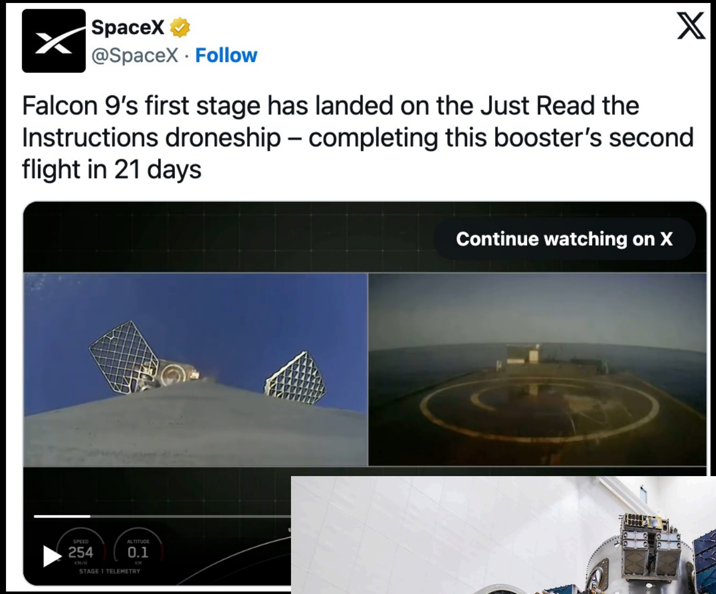
• Establishing pipeline for rapid replenishment

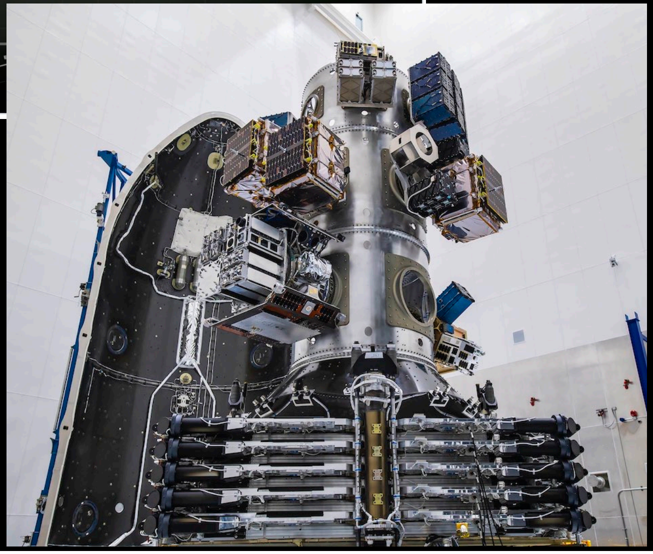
• Innovating launch to meet demand

- Launch supply rising to meet demand[2]

Increasing industry-wide access to space (Rideshare programs)

- "Transporter-1" F9 launch set record for most sats launched on single rocket (143 satellites)[3]



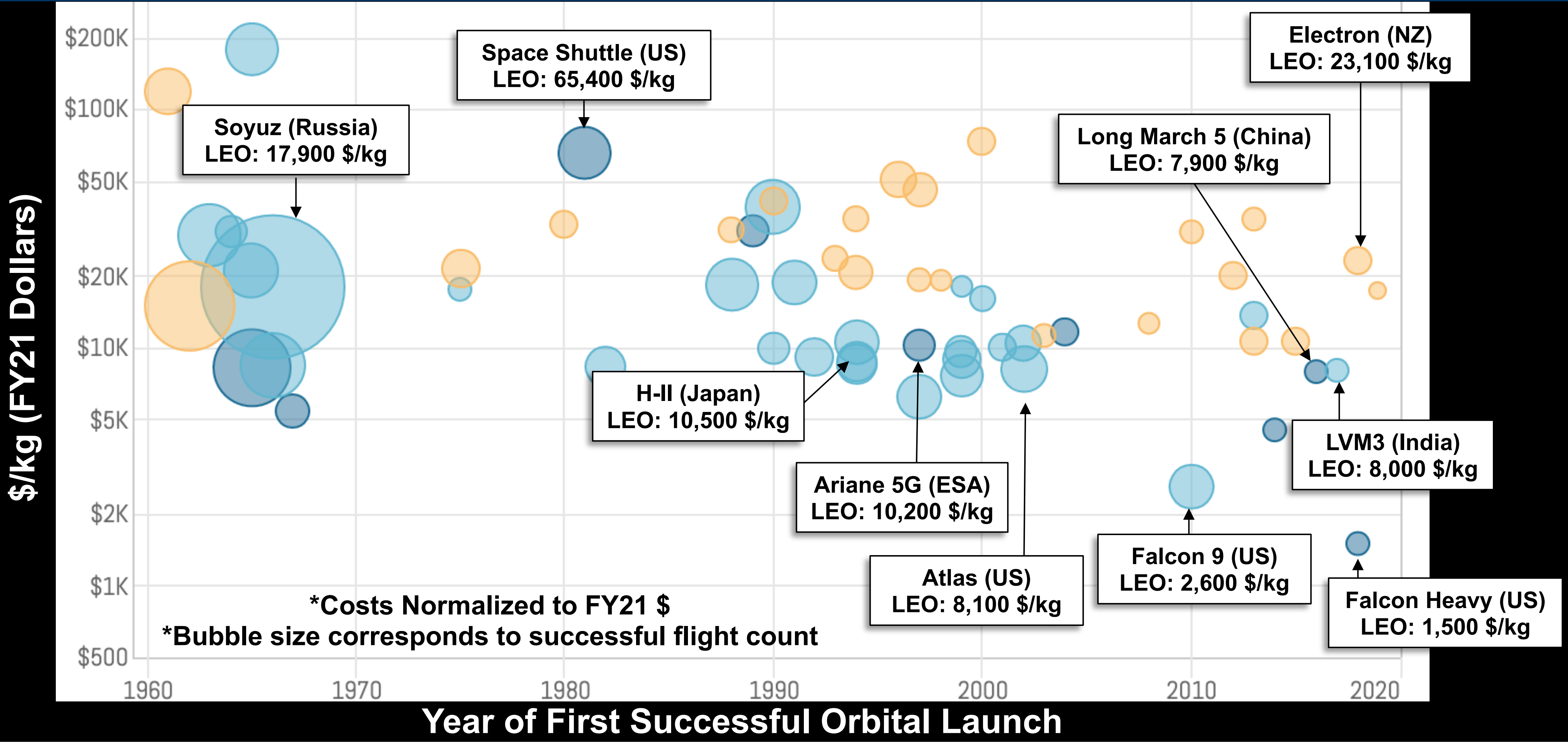


Transporter-1 stack
Credit: SpaceX

1) https://stackoverflow.blog/2021/05/11/building-a-space-based-isp/
2) https://www.teslarati.com/spacex-falcon-9-new-booster-turnaround-record-21-days/
3) https://www.bbc.com/news/science-environment-55775977

Launch Costs Trending Down

Increasing number of countries with launch capabilities and decreasing cost of launch



Credit: CSIS Aerospace Security Project, 2020

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Facilitating Rapid Block Upgrades

Consider long-term manufacturability and upgrade strategy upfront

Reducing information/geographic gates between stakeholders

- What capabilities (engineering, production, etc) can you co-locate?
- What manufacturing capabilities can you bring in-house?

Developing robust ground infrastructure for rapid telemetry evaluation

- What telemetry do you need to make rapid decisions and failure analysis?

Maintaining freedom of choice with vendors

- How do you maintain maximum flexibility with inventory and contracts?

Question: how would you architect your program if a new satellite “block” were rolled out every few weeks?

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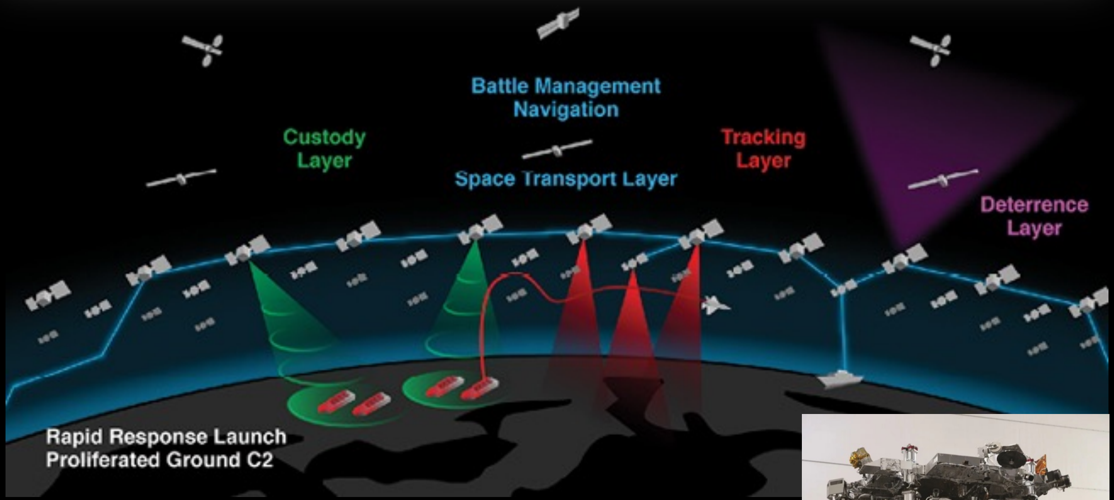
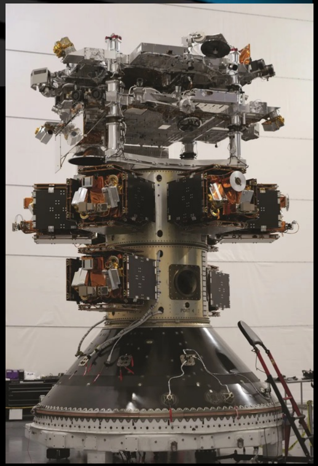
Space Force Incorporating Proliferated Small Sats into Architectures

Space Development Agency (SDA) National Defense Space Architecture

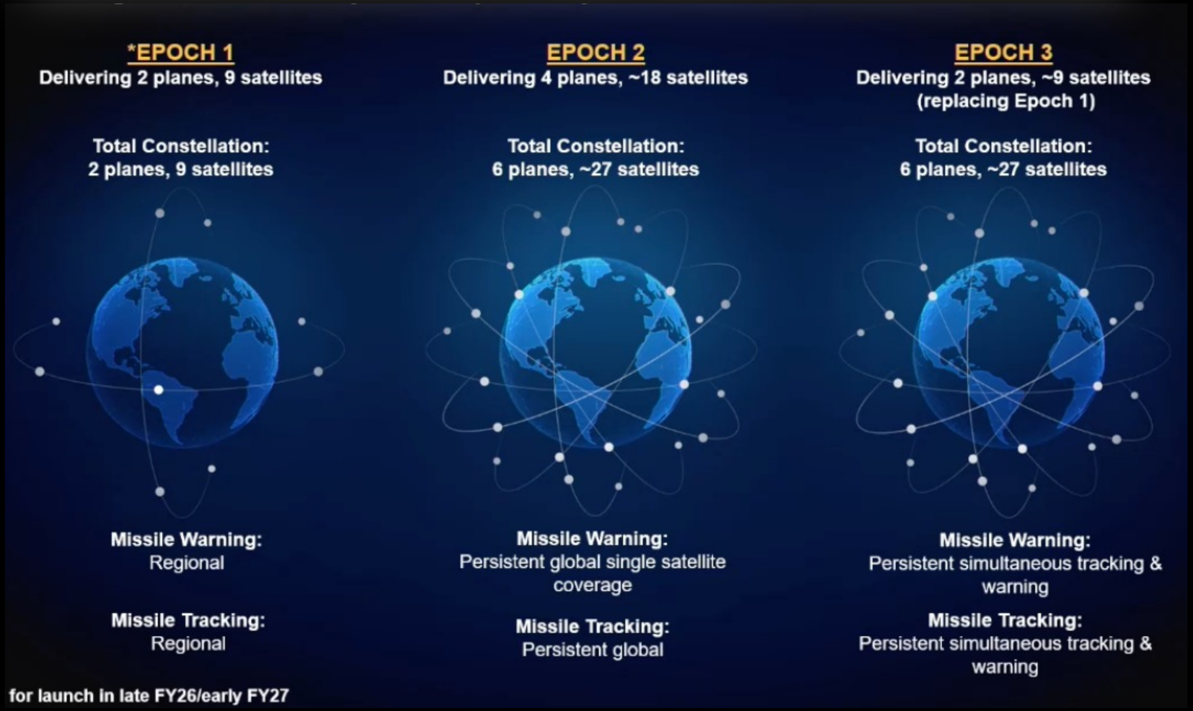


PWSA architectures and its functional layers
Credit: SDA



Delivered satellites for Tranche 0
Credit: York Space Systems

Space System Command's MEO Missile Tracking Layer



Epochs of SSC's missile tracking roll-out
Credit: SSC

Meditations on GEO

Higher risk tolerances lend themselves to orbits with cheaper launch costs and passive disposal options for dead satellites

Question: how can we responsibly leverage responsive space methodologies in GEO?

Thought 1: use LEO as proving ground for GEO

- Assess COTS tech on LEO testbeds → flow into GEO missions
- Requires rapid launch and reconstitution for cost/schedule savings

Thought 2: mixed risk approach

- Responsive techniques for modular payloads, high-reliability posture for safety critical functions

Summary

Responsive space requires rethinking full development cycle

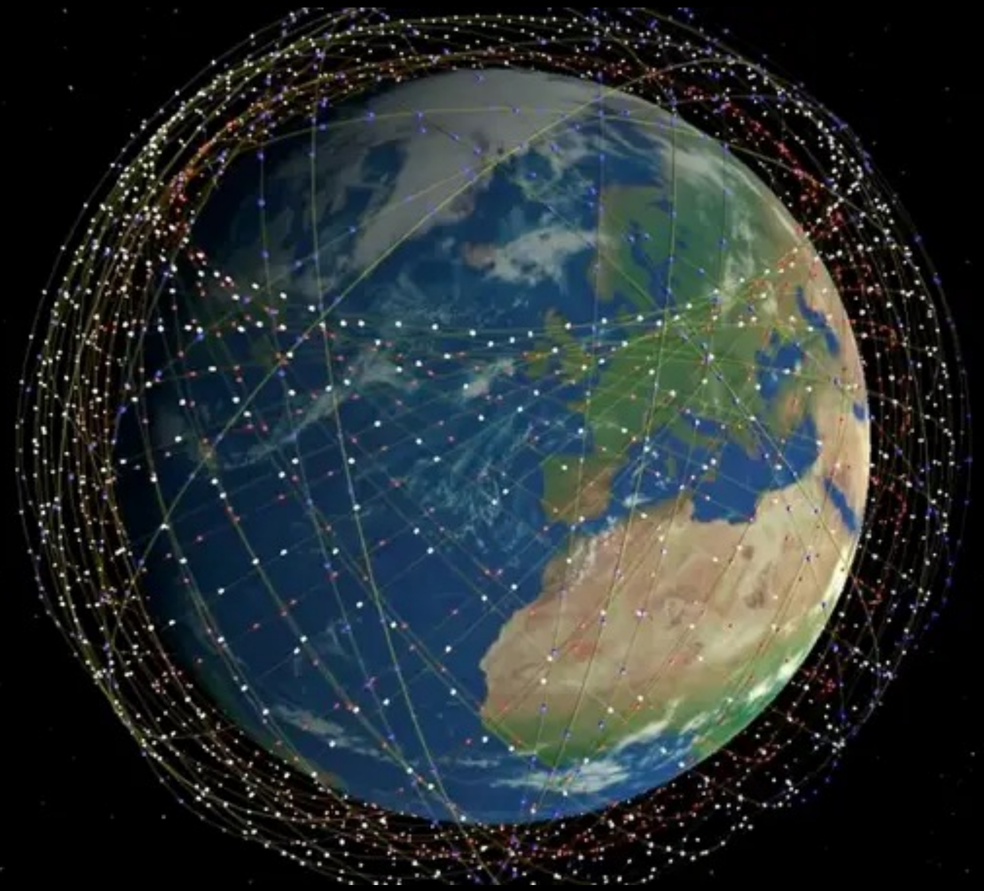


Illustration of Starlink constellation
Credit: Mark Handley University College London

Questions?

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Back-ups

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MITLL Fielding Responsive Space Mission

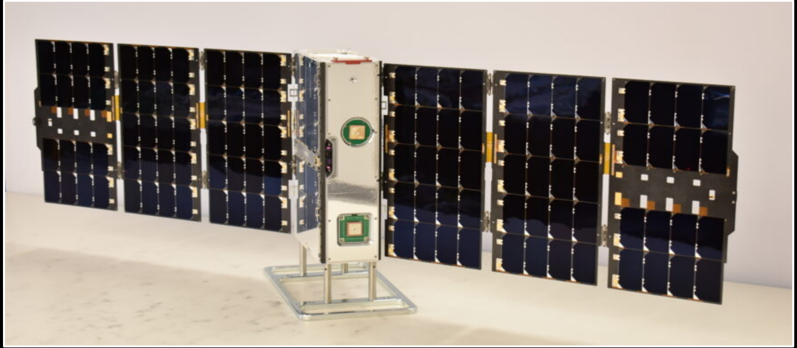
MITLL building capability to field rapid development small sat missions

6U Agile CubeSat Agile MicroSat

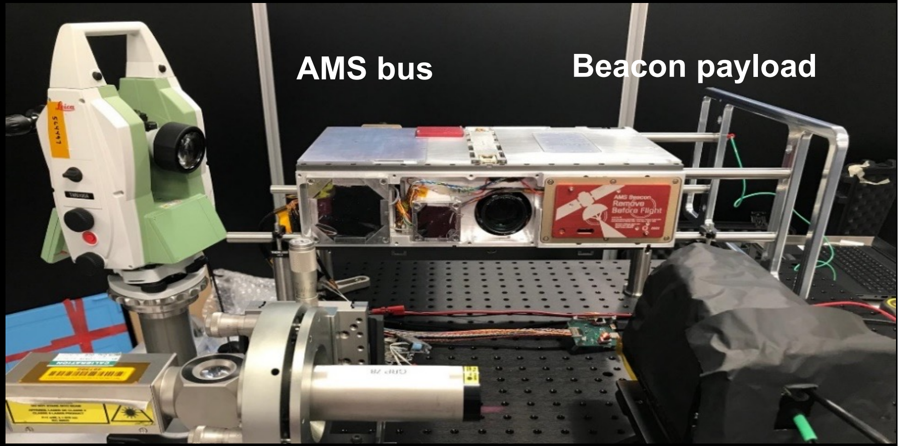
- Purpose: demo low-flying operation (~280 km) & flight qualify experimental payloads (incl Beacon)
- Successful launch May 2022

Beacon = rapid dev program with limited cost & physical resources

- Low cost: <$300k
- Tight schedule: <2 years
- Heavy use of COTS parts
- Design for rapid integration
- Streamlined requirements & testing

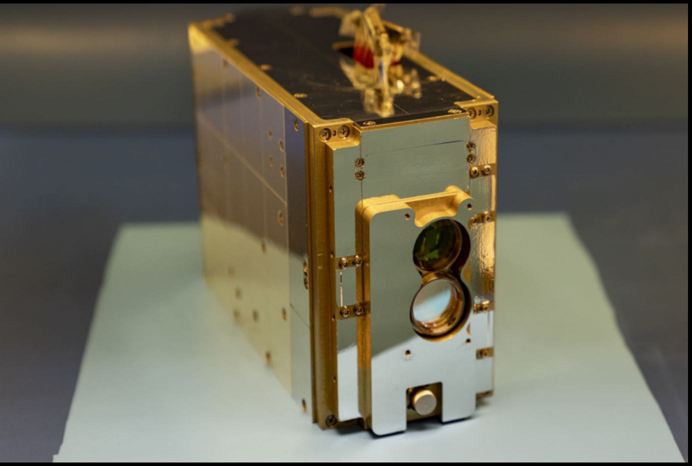


Agile MicroSat
Credit: Blue Canyon Technologies

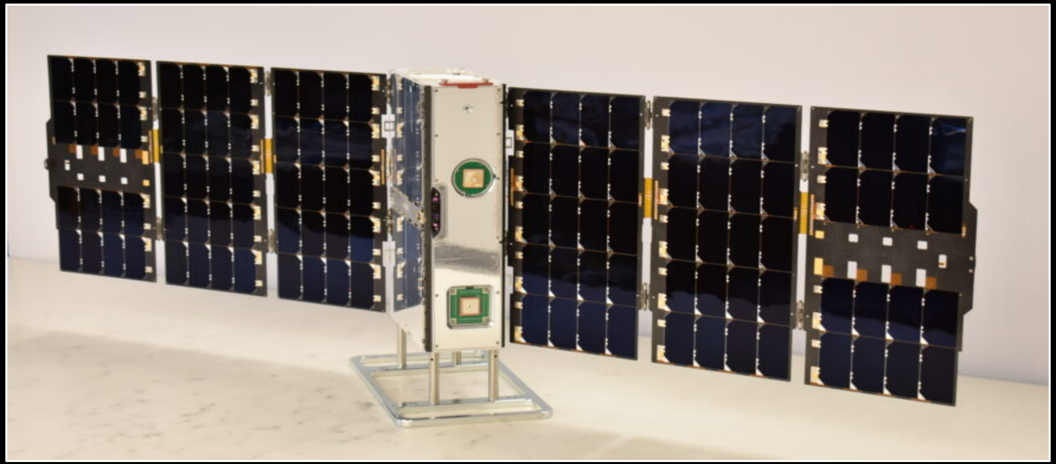


Beacon integrated into Agile MicroSat
Credit: MITLL

MITLL Fielding High Performance Space Payloads

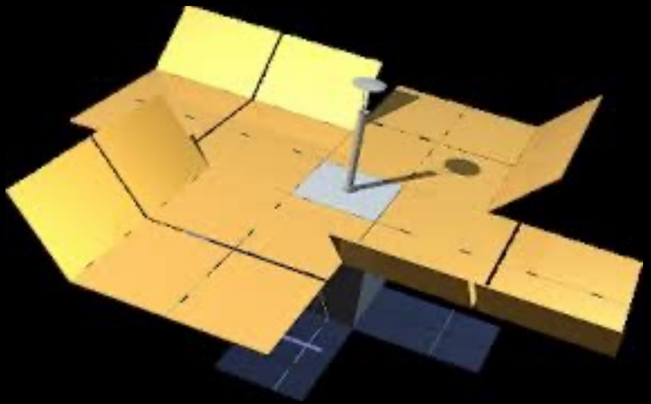


TeraByte InfraRed Delivery (TBIRD) payload onboard CubeSat demo'd record-breaking 100 GB/s ground-space data link
Credit: MIT Lincoln Laboratory



Agile MicroSat demo'd experimental adaptive optics payload and advanced autonomy algorithms for low price point and rapid schedule
Credit: MIT Lincoln Laboratory

Optical comms terminal Illuma-T built to greatly accelerate data transmission from ISS
Credit: MIT Lincoln Laboratory



Deployable Electronically Scanning Reflectarray to offer lightweight, electronically steerable antenna from small sat platform
Credit: MIT Lincoln Laboratory

Situational Awareness Camera Hosted Instrument (SACHI) space domain awareness sensors to be hosted aboard two Japanese partner satellites
Credit: MIT Lincoln Laboratory

Credit: MIT Lincoln Laboratory Technology in Support of National Security 2022 Annual Report

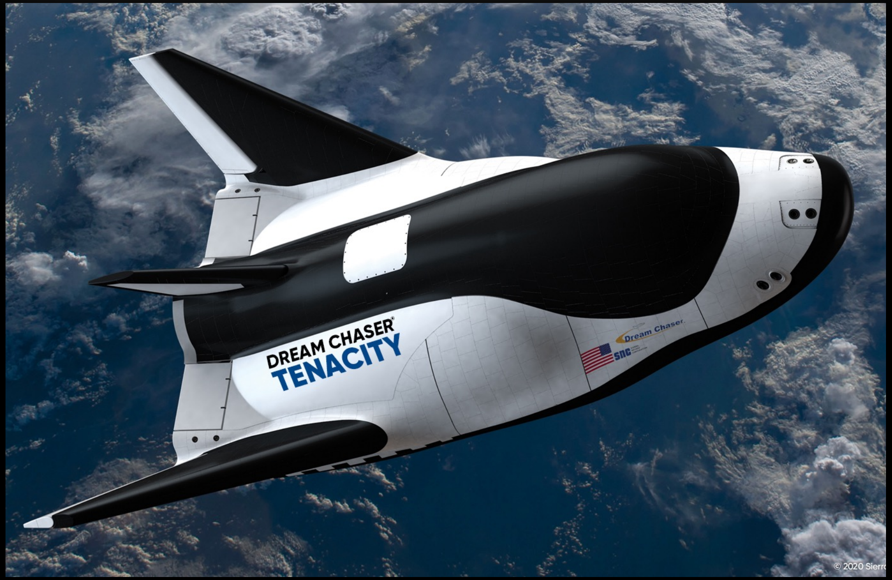
Diversity in Launch Architectures

Many ways to get to space

Growing Commercial Launch Sector

Electron rocket
Credit: Rocket Lab

Reusable Space Planes



Artist illustration of Dream Chaser
Credit: Sierra Nevada Corporation

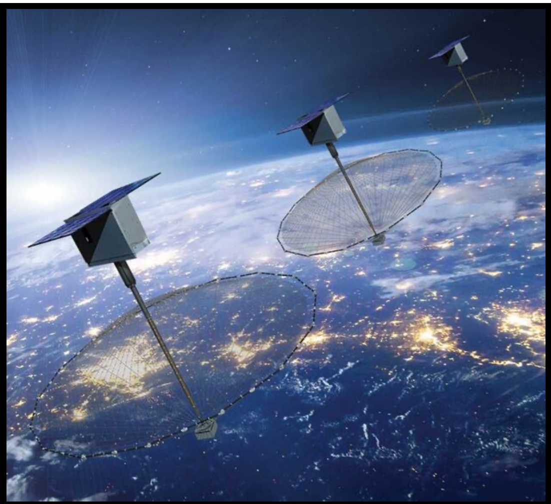
Ground Centrifugal Sling Shot

SpinLaunch architecture overview
Credit: SpinLaunch

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Growing Small Sat Industry Base

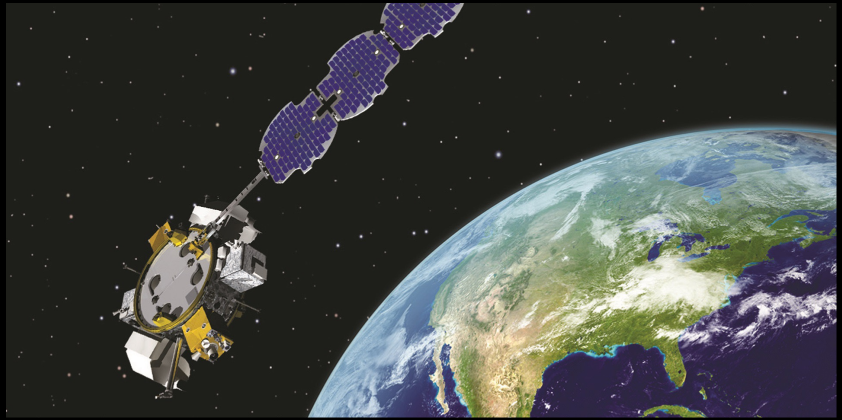
Dove LEO satellite constellation
Credit: Planet Labs



L3Harris High Compaction Ratio Antenna
Credit: L3 Harris

LM400 satellite bus
Credit: Lockheed Martin

Sierra Space small satellites
Credit: SNC



Northrop Grumman's ESPAStar platform
Credit: Northrop Grumman