Engineering Management Program
UNIVERSITY OF COLORADO BOULDER

A VIEW OF AEROSPACE RESEARCH AND DEVELOPMENT OPPORTUNITIES

Dr. Michael Gazarik

Faculty Director (Interim)

Lockheed Martin Endowed Professor

College of Engineering and Applied Science

October 8, 2024

RELEVANT GAZARIK BACKGROUND

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1987

1989

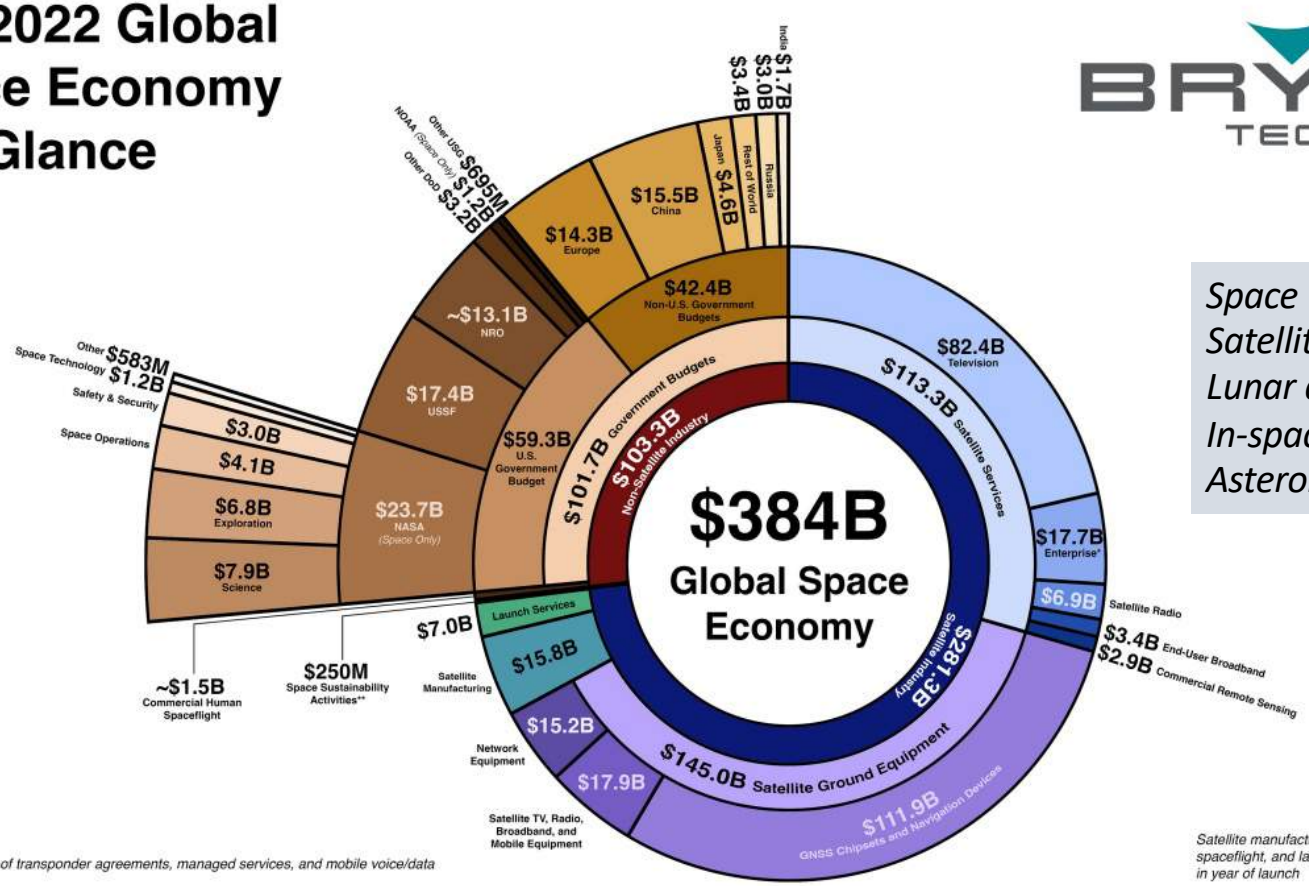
1997

2003

2015

2024

The 2022 Global Space Economy at a Glance



Space Tourism
Satellite Servicing
Lunar activity
In-space manufacturing
Asteroid mining

* *Enterprise consists of transponder agreements, managed services, and mobile voice/data*

** *Space Sustainability Activities consist of debris removal, moving satellites, spacecraft life extension, space situational awareness, satellite servicing, and in-orbit assembly*

Satellite manufacturing, commercial human spaceflight, and launch services revenues counte in year of launch

Numbers may not add up due to rounding

CURRENT STATE OF AFFAIRS

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Artemis

SDA Systems

Proliferated LEO

Photo credit: NASA

Gateway Cislunar

Commercial Lunar Program

International Space Station

Commercial Stations

Photo credit: Boeing Illustration

Photo credit: NASA

VISION-CISLUNAR SPACE

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Photo credit: NASA

Artemis & Gateway

Commercial Station & cis-Lunar

Photo credit: NASA

Looking Forward

VISION

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Flexibility

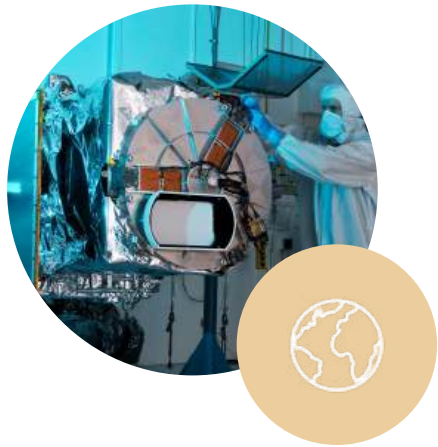
Enabling connectivity across orbits (LEO, GEO, MEO)

Interoperability

Enabling interconnectivity and agile networks for the future

Resilience

Enabling a resilient space infrastructure, with protections against modern cyber threats



Sustainability

Enabling innovative technology for climate risk mitigation and environmental monitoring

CURRENT BARRIERS

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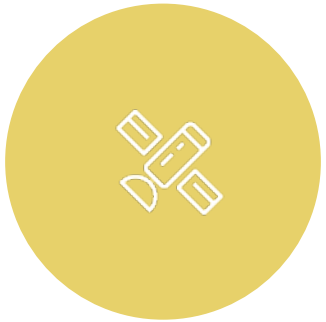
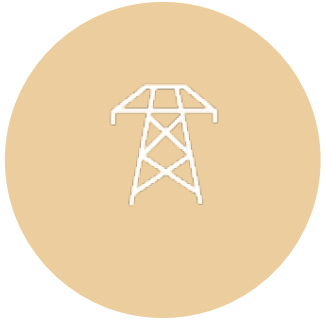
Heritage



Credible Space

How to Buy

Workforce Challenges



Infrastructure

Development Practices

Technology Infusion

Sustainability Challenges

Ground System Development

Cyber Security

HERITAGE

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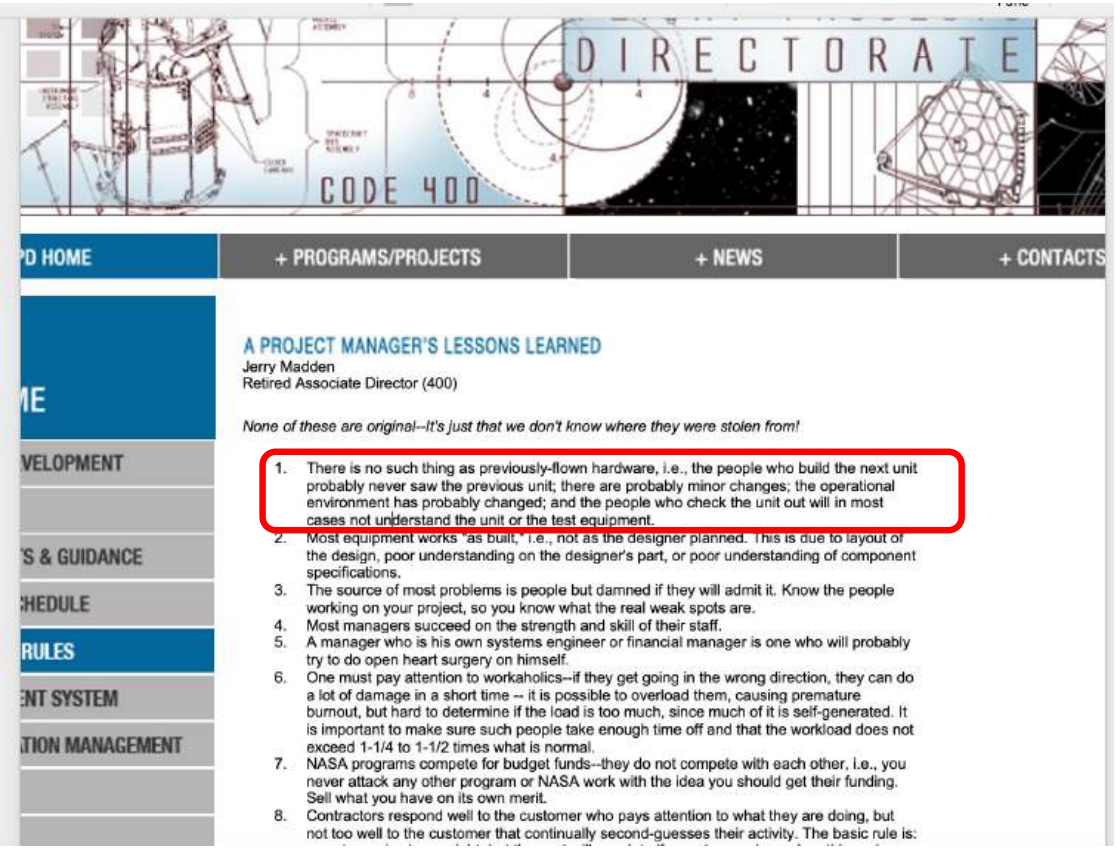
Barrier

- Heritage designs used in different environments can result in challenges and unplanned non-recurring engineering

- Perhaps, also impair infusion of new technology.

How to overcome?

Use smartly and move to modular systems



Credit: Jerry Madden, NASA

CREDIBLE SPACE

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Barrier

- Learn from successes
- Failures can slow us all down
- Watch the oversell

How to overcome?

Build credible systems, build off each other's successes

Left: Air Pollution tester TEMPO Credit: Maxar; Top Right: Ball technician works on The Green Propellant Infusion Mission satellite

HOW TO BUY

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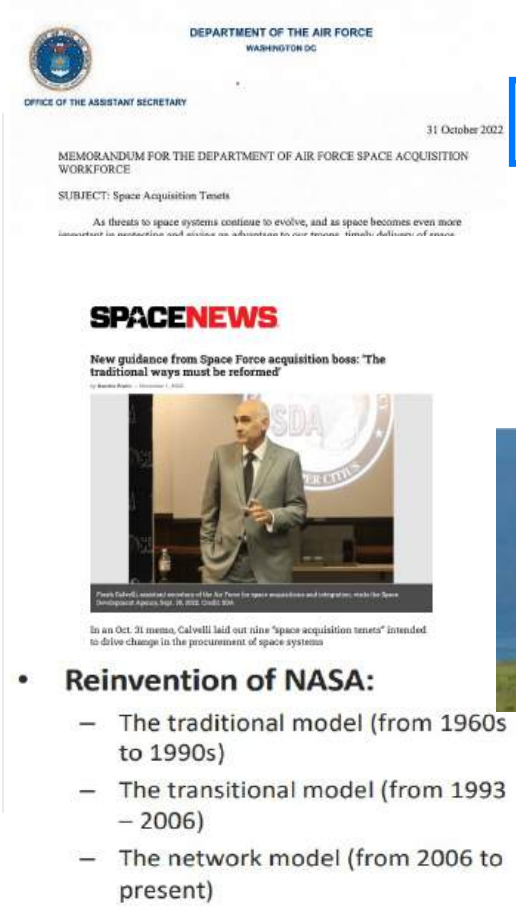
Barrier

- Mounting pressure to purchase and deliver on accelerated timelines
- OTA Utilization up 15X (2015-2021, McKinsey & Company)
- Cis-lunar and LEO will be developed via service-based contracts

How to overcome?

- Develop paths through our FAR-based organizations & partner
- Develop trust with buyers co-learning along the way


DEPARTMENT OF THE AIR FORCE
WASHINGTON DC

OFFICE OF THE ASSISTANT SECRETARY

31 October 2022

MEMORANDUM FOR THE DEPARTMENT OF AIR FORCE SPACE ACQUISITION WORKFORCE

SUBJECT: Space Acquisition Tenets

As threats to space systems continue to evolve, and as space becomes even more

SPACENEWS

New guidance from Space Force acquisition boss: 'The traditional ways must be reformed'

In an Oct. 31 memo, Calvelli laid out nine "space acquisition tenets" intended to drive change in the procurement of space systems

- **Reinvention of NASA:**
  - The traditional model (from 1960s to 1990s)
  - The transitional model (from 1993 – 2006)
  - The network model (from 2006 to present)


Build smaller satellites, smaller ground systems and minimize non-recurring engineering. Use existing technology and designs. Acquire ground and software intensive systems in smaller more manageable pieces that can be delivered faster.

Get the acquisition strategy correct, including contract type and contract incentives for both speed and performance. Have clear, specific, unambiguous statements of work, minimize and avoid government furnished equipment and avoid putting the government in the middle of multiple contracts as the integrator. Do not be afraid to use fixed price contracts.

Enable teamwork between contracting officers and program managers, and they preferably should be collocated.

Award contracts with realistic cost and schedule targets to avoid low bids and buy-ins. Ensure companies have the correct skills to successfully execute the contract. Understand what companies are capable of doing or not doing.

Maintain stability in programs. Push back on year-to-year budget changes that drive rebaselining and slow down acquisitions. Avoid accepting new requirements after going on contract.

Avoid over-classifying. Putting programs in the "special access program" category hinders the integration of space capabilities across other domains and can hinder getting ideas from a broader pool of industry. Avoid classifying systems as "no foreign" to enable future sharing with allies.

Deliver ground before launch. Ensure ground systems are completed and ready for operations before launch of a new capability.

The Reinvention of NASA
•by Loizos Heracleous,
• Douglas Terrier,
• and Steven Gonzalez
April 23, 2018

Credit: NASA 2018, Air Force, 2022, Space News, 2022

WORKFORCE CHALLENGES

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Barrier

- Aerospace workforce shortage
- Need to broaden reach to attract tomorrow's talent

How to overcome?

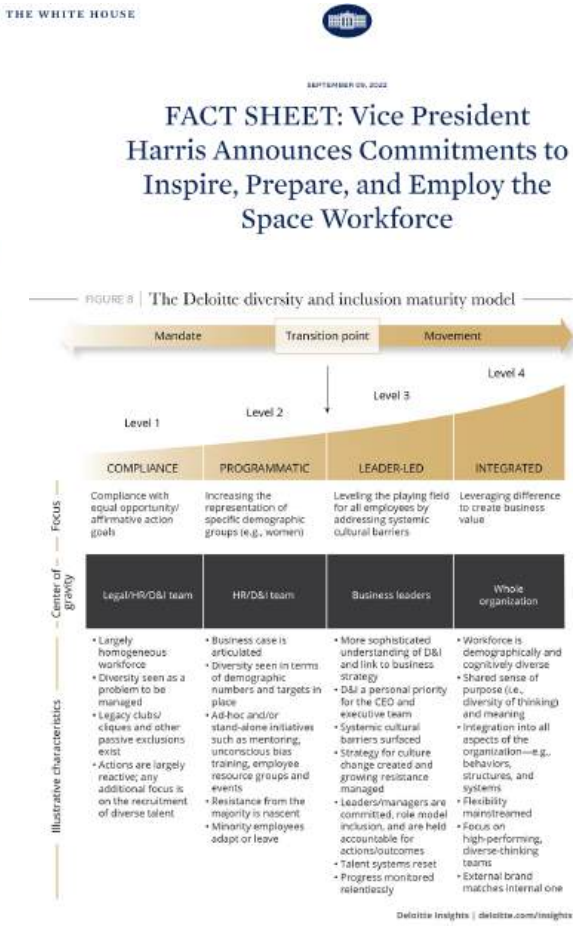
- Double down on *Diversity and Inclusion* efforts and strategy
- Form regional hubs

SPACENEWS

Space industry CEOs pledge to create more inclusive workforce

Companies said they will 'significantly increase the number of women and employees from underrepresented groups'

COLORADO SPRINGS – Top executives from the space industry on April 5 signed a pledge to advance diversity across the workforce.



THE WHITE HOUSE

FACT SHEET: Vice President Harris Announces Commitments to Inspire, Prepare, and Employ the Space Workforce

FIGURE 8 | The Deloitte diversity and inclusion maturity model

	Mandate	Transition point	Movement	
	Level 1	Level 2	Level 3	Level 4
	COMPLIANCE	PROGRAMMATIC	LEADER-LED	INTEGRATED
Focus	Compliance with equal opportunity/ affirmative action goals	Increasing the representation of specific demographic groups (e.g., women)	Leveling the playing field for all employees by addressing systemic cultural barriers	Leveraging difference to create business value
Center of gravity	Legal/HR/D&I team	HR/D&I team	Business leaders	Whole organization
Illustrative characteristics	• Largely homogeneous workforce • Diversity seen as a problem to be managed • Legacy clubs/ cliques and other passive exclusions exist • Actions are largely reactive; any additional focus is on the recruitment of diverse talent	• Business case is articulated • Diversity seen in terms of demographic numbers and targets in place • Ad-hoc and/or stand-alone initiatives such as mentoring, unconscious bias training, employee resource groups and events • Resistance from the majority is nascent • Minority employees adapt or leave	• More sophisticated understanding of D&I and link to business strategy • D&I a personal priority for the CEO and executive team • Systemic cultural barriers surfaced • Strategy for culture change created and growing resistance managed • Leaders/managers are committed, role model inclusion, and are held accountable for actions/outcomes • Talent systems reset • Progress monitored relentlessly	• Workforce is demographically and cognitively diverse • Shared sense of purpose (i.e., diversity of thinking) and meaning • Integration into all aspects of the organization—e.g., behaviors, structures, and systems • Flexibility mainstreamed • Focus on high-performing, diverse-thinking teams • External brand matches internal one

Deloitte Insights | deloitte.com/insights

Credit: Triangle DEI Blog, 2020, White House, 2022, SpaceNews 2022, EY 2022

INFRASTRUCTURE

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Barrier

- Space assets expected to grow, need infrastructure to keep pace
- Lack of standard interfaces & protocols

How to overcome?

- Standards and sharing
- Develop with space and infrastructure in-mind
- Build off each other's capabilities
- Work with partners to build future groundwork

Credit: Aerospace Defense Forum, 2015

DEVELOPMENT PRACTICES

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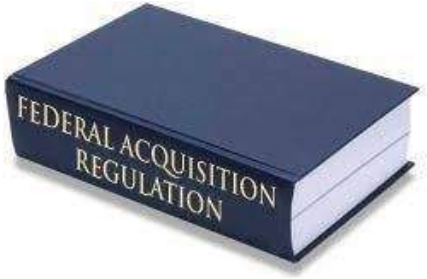
Barrier

- How to execute non-FAR in a FAR based organization?
- Where to take risks?
- Flight rules serves us well until now

How to overcome?

- Tailoring doesn't work
- Embrace new flight rules for development practices



Left: WSF-M Microwave Imager (MWSI) Integration and Test; Top Right: Ball Aerospace developed an ESPA-class standard interface vehicle for the U.S. Air Force Space Test Program

Credit: NASA 2021

TECHNOLOGY INFUSION

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Barrier

- Can be challenging to address issues & risks from mission owners and gain their buy-in
- Embrace new technology from partners

How to overcome?

- Demonstrate and infuse technology development – fly early and often
- Include mission stakeholders

Left: Technology Infusion Credit: Via Satellite archives Top Right: Ball Aerospace's Rideshare launching on a SpaceX Falcon 9 Credit: Kinesis

SUSTAINABILITY

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Barrier

- Infrastructure challenges currently exist
- Standards still needed to address orbital debris
- What is the paradigm to service and clean?

How to overcome?

- Technology not the barrier anymore. Regulatory & ownership
- Build products with re-use and infrastructure in-mind

Left: Orbital debris Credit: Smithsonian Magazine; Top Right: ESA active debris removal Credit: European Space Agency

GROUND SYSTEM DEVELOPMENT

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Barrier

- Space assets expected to grow, ground system architecture needs to scale and integrate
- Ground systems still often remain a challenge post-launch

How to overcome?

- Modern software architectures and practices
- Double-down on workforce & training

Left: Ball Aerospace ground systems;
Top Right: Near Field Range

CYBER SECURITY

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Barrier

- Cyber security is a rising challenge, will need trust in the supply chain

How to overcome?

- Double down on knowledge transfer and standards
- Workforce development & human resource considerations

POLICY

Here's the Pentagon's New Plan to Woo and Retain Cyber Workers

The 2023-27 strategy aims to improve identification, recruitment, development, and retention of civilians in IT and related jobs.

OCTOBER 11, 2022

FACT SHEET: Biden-Harris Administration Delivers on Strengthening America's Cybersecurity

Credit: Defense News, 2023, White House, 2022

SHUTTLE RETIREMENT

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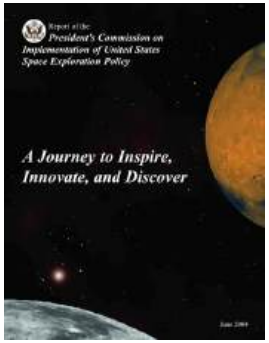
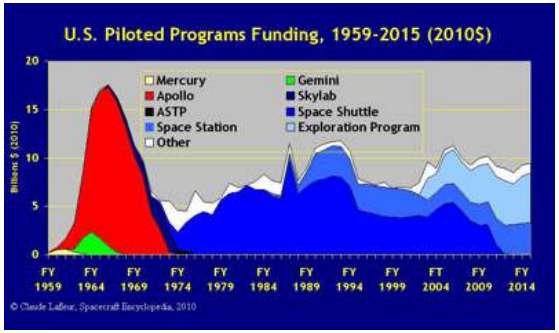
- Decision made in 2004 under President Bush *Vision for Space Exploration*
- Constellation Program era begins
  - Ares I and Ares V rockets based on re-use of shuttle subsystems: main engines, boosters and external tank
  - Altair Lunar Lander
  - Orion crewed vehicle
- Atlantis flew last flight in July 2011
- Complete reliance on Russian partners to reach International Space Station – no US capability


NEWS

BUSH'S NASA PLAN CALLS FOR SHUTTLE'S RETIREMENT

By Gwyneth K. Shaw and Sentinel Staff Writer
Orlando Sentinel • Jan 13, 2004 at 12:00 am





COMMERCIAL SERVICES BEGIN

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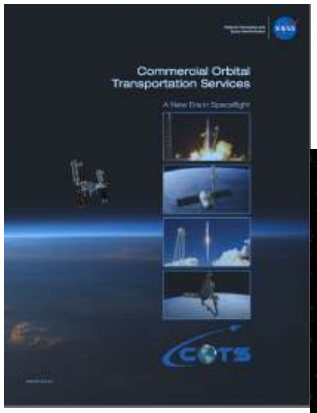
- Commercial Orbital Transportation Services (COTS) starts in January 2006, ends Sept 2013
  - Orbital Sciences
  - SpaceX - after a protest; $396M
  - $800M investment results in two new US capabilities: launch and vehicle
- Commercial Resupply Services (CRS) in 2008
  - Purchase of a service vs managed development of a vehicle and rocket
  - 8 flights from Orbital $1.9B
  - 12 flights from SpaceX for $1.6B
  - First commercial vehicle to fly to the ISS in October 2012
- Radical concept from previous historic achievements at NASA – use of Space Act Agreements



CONSTELLATION PROGRAM CANCELLATION

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- Augustine Report recommended cancelation largely because of cost concerns
- 2011 President Budget Request released in February 2010 proposed cancelation of the program
- The stage was set…

SPACE & PHYSICS

Phased Out: Obama's NASA Budget Would Cancel Constellation Moon Program, Privatize Manned Launches

The president wants to scrap NASA's space shuttle successor, now in development, and relax the agency's focus on returning to the moon

By John Matson on February 1, 2010

Obama Made Mistake Cancelling NASAs Constellation; Sen. Bill Nelson

AUGUSTINE COMMITTEE: CURRENT NASA HUMAN SPACE FLIGHT PROGRAM ON "UNSUSTAINABLE TRAJECTORY"

By Marcia Smith | Posted: September 8, 2009 12:00 am ET | Last Updated: December 5, 2011 6:12 pm ET

THE COMPROMISE

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- 2011 Budget Request: Stalemate – no funds for Commercial Cargo and Crew and Space Technology
- The Sept 2011 "SLS" Deal
  - Brokered by Senator Nelson and Senator Kay Bailey Hutchinson
  - Orion and Space Launch System in parallel with Commercial approach
  - Space Technology receives inaugural funding
- Today – launched Nov 16, 2022
  - About $50B invested

After years of setbacks, NASA's SLS moon rocket is ready to fly

By Christian Davenport
August 27, 2022 at 6:00 a.m. EDT

The SLS rocket is the worst thing to happen to NASA—but maybe also the best?
"This has been a really tough thing."
ERIC BERGER - 8/23/2022, 5:30 AM

SPACEX CHANGES EVERYTHING

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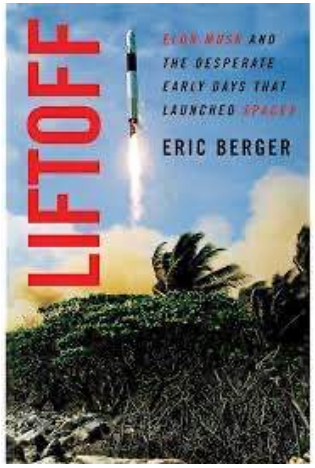
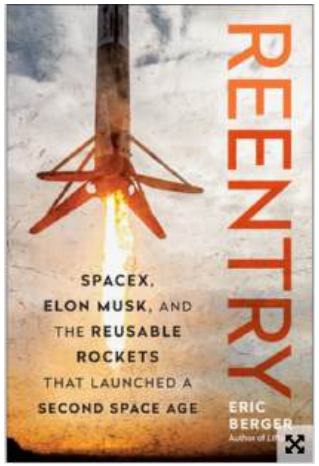
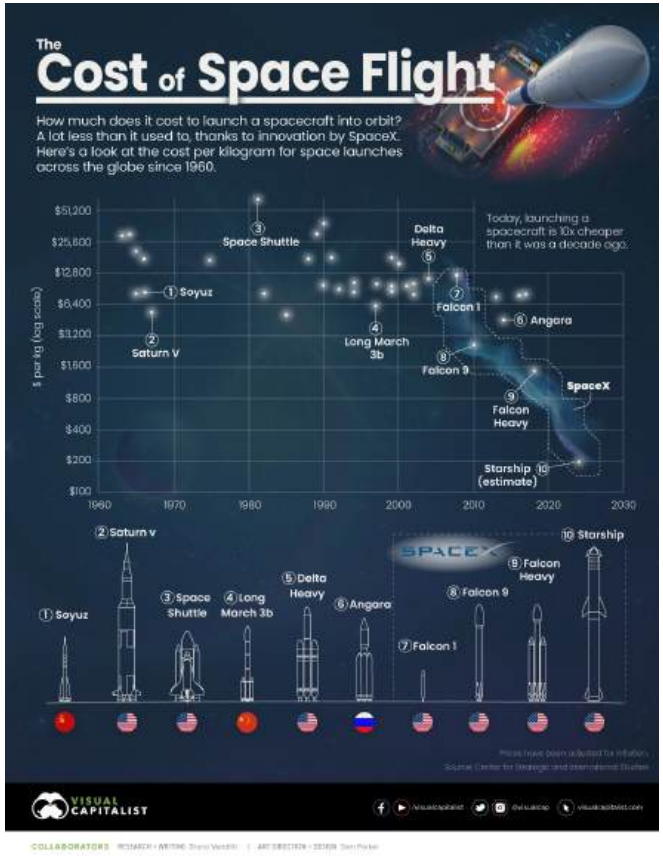
- SpaceX has revolutionized the launch industry and access to space
- Falcon 1 story (4 attempts)
- Falcon 9 and Falcon 9 Heavy
- Starship
- Many non-believers in the beginning (and some still today)
- Demonstrated the viability of re-use
- Reduced cost per kg substantially







DRIVING FACTORS FORCING CULTURE CHANGE

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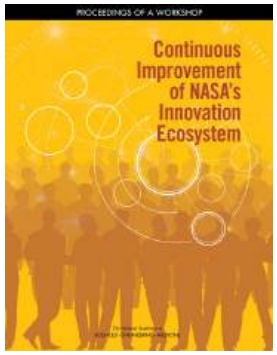
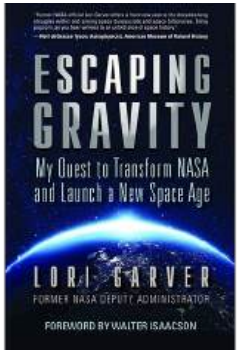
- Changing of culture from oversight/insight of development to acquisition of services
- Space community has changed
- Can the Agency adapt and leverage the space industrial base and community?
- **Reinvention of NASA:**
  - The traditional model (from 1960s to 1990s)
  - The transitional model (from 1993 – 2006)
  - The network model (from 2006 to present)

After space shuttle program, NASA's future still bright
Progress in technology, national security requires continued investment in space program

Waleed Abdalati & Robert Braun - Baltimore Sun
(Abdalati is NASA's chief scientist & Braun is NASA's chief technologist)

With the Shuttle Program Ending, Fears of Decline at NASA
William Broad - New York Times **Circa July 2011**





COMMERCIAL STATION AND LEO

- International Space Station set to retire in 2031
- The commercial services construct continues
- Axiom also developing commercial station leveraging the current ISS

NASA Selects Companies to Develop Commercial Destinations in Space December 2021

NASA has signed agreements with three U.S. companies to develop designs of space stations and other commercial destinations in space. The agreements are part of the agency's efforts to enable a robust, American-led commercial economy in low-Earth orbit.

•Blue Origin of Kent, Washington, for $130 million
•Nanoracks LLC, of Houston for $160 million
•Northrop Grumman Systems Corporation of Dulles, Virginia, for $125.6 million

Merged

COMMERCIAL CIS-LUNAR

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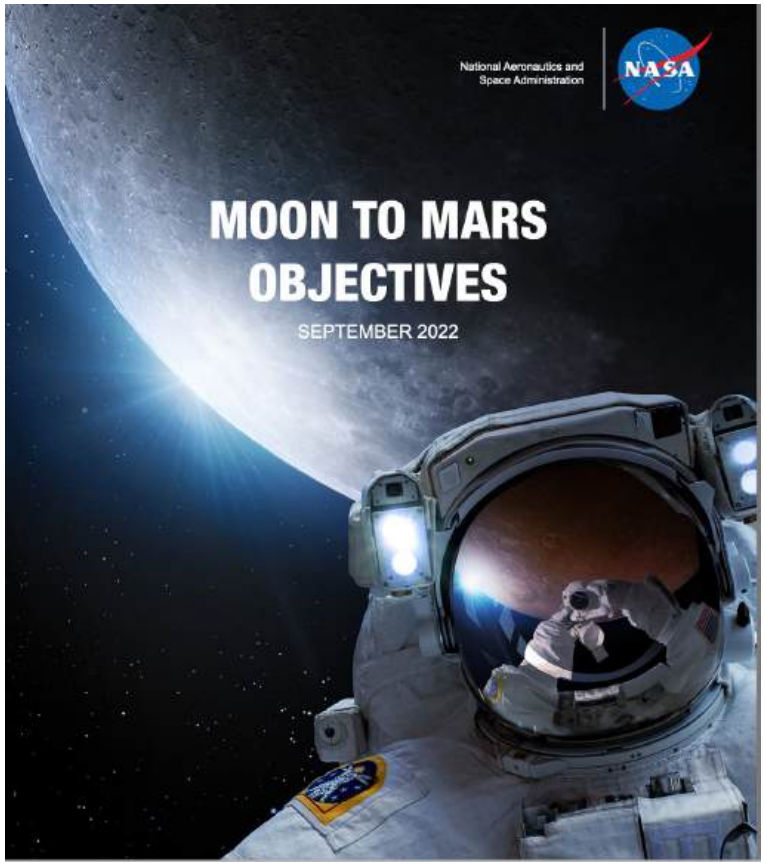
- Lunar Lander
  - SpaceX Human Landing Systems (HLS) selected as sole provider to land crews on moon for $2.9B
- Commercial Lunar Payload Services Program
  - …beginning in 2022 will perform science experiments, test technologies and demonstrate capabilities to help NASA explore the Moon and prepare for human missions.
  - CLPS contracts are indefinite delivery, indefinite quantity contracts with a cumulative maximum contract value of $2.6 billion through 2028

Apr 16, 2021
RELEASE 21-042
As Artemis Moves Forward, NASA Picks SpaceX to Land Next Americans on Moon

Nov 4, 2021
RELEASE 21-146
NASA Statement on Artemis Lunar Lander Court Decision

LOOKING FORWARD

- Will commercial station developments mature as expected?
  - Will the business case hold?
- Will the services model succeed in LEO and cis-lunar?
- When and how often will SLS fly?
- Will Starship change everything?



A NASA PERSPECTIVE

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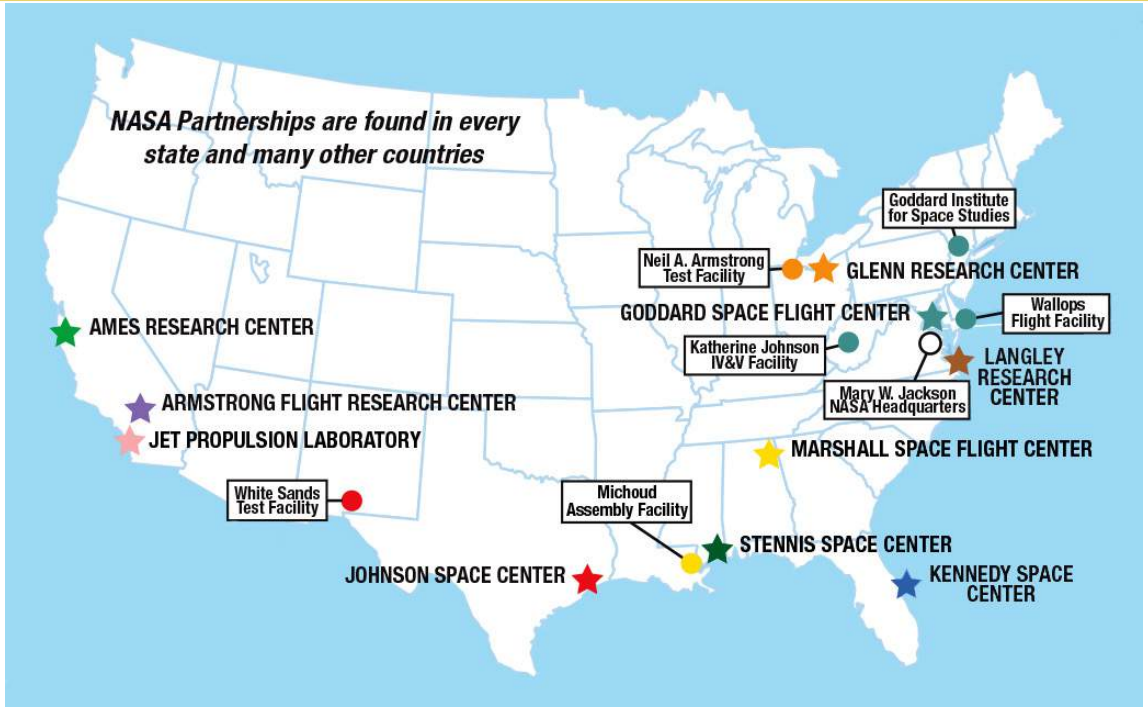
- Thoughts on culture
- How to handle engaging the 10 centers and 18,000 civil servants
  - Opportunity!
- Executing Missions
- Executing Roadmaps
- Public Private Partnerships
- Shifting to Services
  - Commercial Cargo
  - Commercial Crew
  - Commercial LEO stations
  - Commercial Lunar



NASA MISSION DIRECTORATES

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Aeronautics

$966M

Space Technology

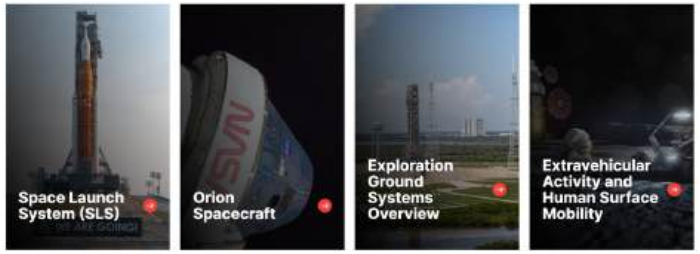
$1182M

Science

$7566M

Space Operations

$4390M



Exploration Systems Development

$7618M

NASA's FY 2025 Budget Request

Budget Authority ($M)	FY 2023 Operating Plan[1/]	FY 2024 CR[2/]	FY 2025 Request	FY 2025 Request			
				FY 2026	FY 2027	FY 2028	FY 2029
Deep Space Exploration Systems	7,447.6	7,468.9	**7,618.2**	7,803.7	7,959.8	8,119.0	8,281.4
Moon to Mars Transportation System	4,716.6		[illegible]	4,254.0	4,267.3	3,880.9	3,713.6
Moon To Mars Lunar Systems Development	2,630.5		3,288.1	3,285.7	3,389.5	3,868.8	3,712.3
Human Exploration Requirements & Architecture	100.5		[illegible]	264.1	303.0	369.3	855.5
Space Operations	4,266.7	4,250.0	**4,389.7**	4,497.6	4,587.6	4,679.4	4,773.0
International Space Station	1,286.2		1,269.6	1,267.8	1,262.8	1,259.4	1,259.4
Space Transportation	1,759.6		1,862.1	1,876.2	1,840.9	1,895.7	1,804.1
Space and Flight Support	983.4		1,088.4	1,051.3	1,048.7	1,059.0	1,080.2
Commercial LEO Development	224.3		169.6	302.3	435.2	465.2	629.3
Exploration Operations	13.2		[illegible]	0.0	0.0	0.0	0.0
Space Technology	1,193.0	1,200.0	**1,181.8**	1,205.4	1,229.5	1,254.1	1,279.2
Science	7,791.5	7,795.0	**7,565.7**	7,717.0	7,871.3	8,028.7	8,189.3
Earth Science	2,175.0		[illegible]	2,396.3	2,446.1	2,489.7	2,543.4
Planetary Science	3,216.5		2,731.5	2,850.5	2,911.6	2,976.8	3,042.5
Astrophysics	1,510.0		1,578.1	1,587.0	1,613.6	1,647.1	1,673.4
Heliophysics	805.0		786.7	791.9	807.0	820.3	833.4
Biological and Physical Sciences	85.0		90.8	91.3	93.0	94.8	96.6
Aeronautics	935.0	935.0	**965.8**	985.1	1,004.8	1,024.9	1,045.4
STEM Engagement	143.5	143.5	**143.5**	146.4	149.3	152.3	155.3
Safety, Security, and Mission Services	3,136.5	3,129.5	**3,044.4**	3,105.3	3,167.4	3,230.7	3,295.3
Mission Services & Capabilities	2,067.4		2,058.1	2,099.2	2,141.3	2,184.1	2,227.6
Engineering, Safety, & Operations	1,069.1		986.3	1,006.1	1,026.1	1,046.6	1,067.7
Construction and Environmental Compliance & Restoration	422.4	414.3	**424.1**	379.3	386.9	394.6	402.5
Construction of Facilities	346.2		344.7	298.3	304.3	310.4	316.6
Environmental Compliance and Restoration	76.2		79.4	81.0	82.6	84.2	85.9
Inspector General	47.6	47.6	**50.5**	51.5	52.5	53.6	54.7
NASA Total	25,383.7	25,383.7	25,383.7	25,891.3	26,409.1	26,937.3	27,476.1

1/ - FY 2023 reflects amounts in Public Law 117-328, Consolidated Appropriations Act, 2023, adjusted by NASA's September 2023 Operating Plan, plus $8M for IT Modernization Working Capital Fund.
2/ - FY 2024 reflects annualized funding amounts based on funding specified in Public Law 117-328, Consolidated Appropriations Act, 2023.

NASA SCIENCE

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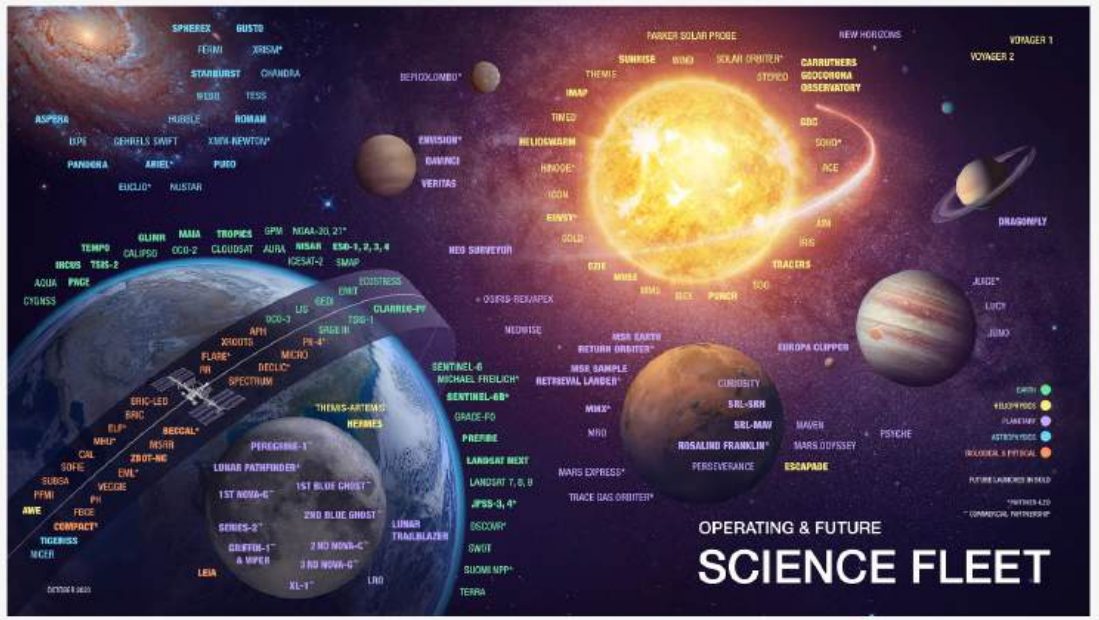
UNIVERSITY OF COLORADO BOULDER

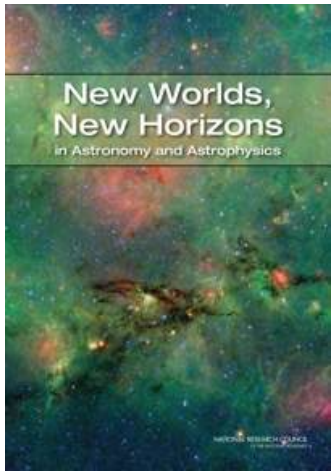
- Organized into major areas
  - Earth
  - Planetary
  - Astrophysics
  - Heliophysics
  - Biological and Physical Sciences
- **Missions**
- **Research Opportunities in Space and Earth Sciences 2024 (ROSES-2024)**

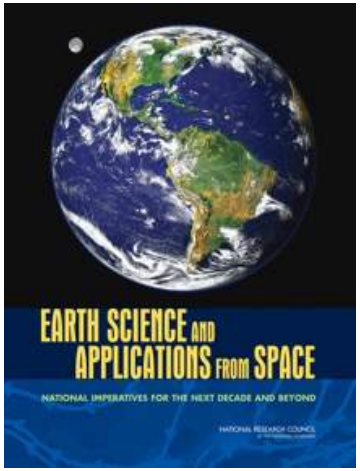


Updated October 2023

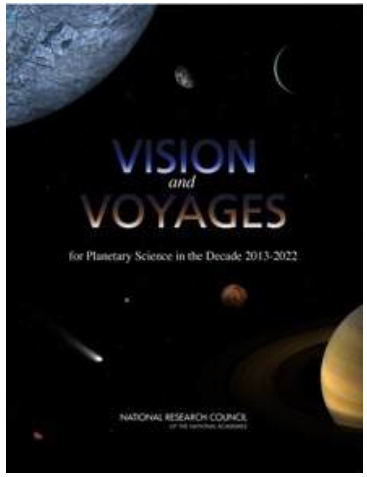
- https://nspires.nasaprs.com/external/solicitations/summary.do?solId=%7B600EE5E5-E9D5-FF55-0CAD-764F6D4BEEA9%7D&path=&method=init

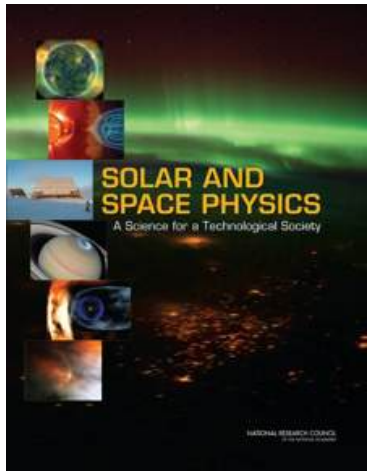
Decadal Surveys



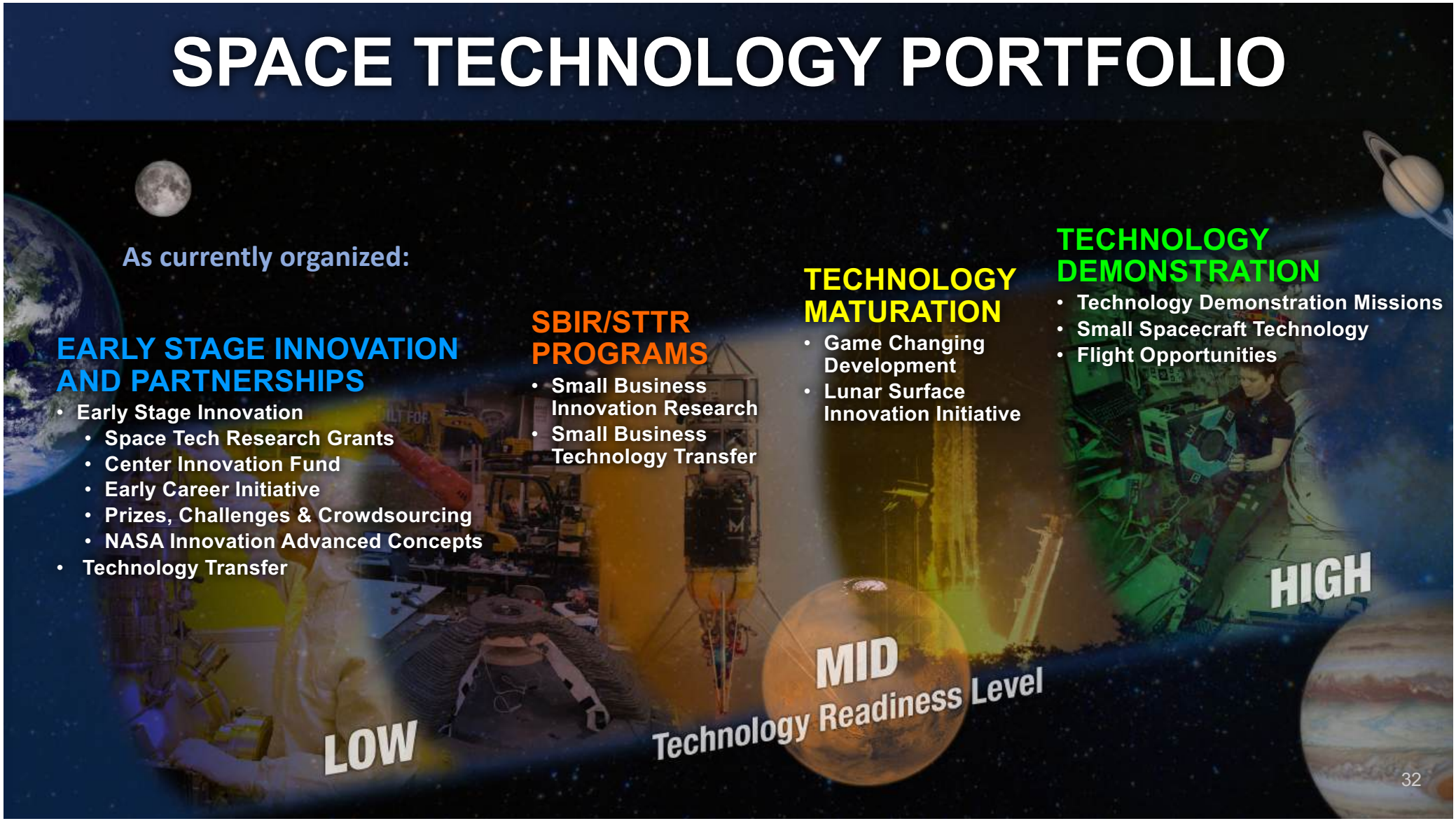


- Each Mission Directorate commissions the National Academy of Science's (NAS) National Research Council to construct Decadal Surveys
- Provides guidance, not prescription:
  - Asynchronous
  - Mid-term updates
  - Sometimes overtaken by events
- Lots of subcommittees, White Papers, academic campaigning
- NASA relies heavily on content
  - Provides "North Star"
  - Provides science-based "top-cover"
  - Externalizes strategic planning
- See also
  - NAS Space Studies Board
  - Int'l Committee on Space Research (COSPAR)





SPACE TECHNOLOGY PORTFOLIO



As currently organized:

EARLY STAGE INNOVATION AND PARTNERSHIPS

- Early Stage Innovation
  - Space Tech Research Grants
  - Center Innovation Fund
  - Early Career Initiative
  - Prizes, Challenges & Crowdsourcing
  - NASA Innovation Advanced Concepts
- Technology Transfer

SBIR/STTR PROGRAMS

- Small Business Innovation Research
- Small Business Technology Transfer

TECHNOLOGY MATURATION

- Game Changing Development
- Lunar Surface Innovation Initiative

TECHNOLOGY DEMONSTRATION

- Technology Demonstration Missions
- Small Spacecraft Technology
- Flight Opportunities

LOW

MID

HIGH

Technology Readiness Level

Tech Base Functional Domains

GO
Space Transportation

- Advanced Propulsion
- Nuclear Propulsion
- Flight Vehicle Systems (including Ascent Systems)
- Cryogenic Fluid Management

LAND
Space to Surface Operations

- Deceleration Systems
- Guidance & Nav Systems
- Landing Systems & Environments
- Entry Modeling & Instrumentation

LIVE
Surface Infrastructure/ Exploration

- Surface Power
- In Situ Resource Utilization
- Surface Structures & Construction
- Dust Mitigation & Environments
- Surface Mobility & Transportation
- Surface Habitation Systems
- Surface Sustainability & Logistics

EXPAND
In-Space Infrastructure/ Discovery

- Observation Systems
- In-Space Sustainability
- Communications, Positioning, Navigation, & Timing
- In-Space Servicing Assembly & Manufacturing
- Small Spacecraft & Distributed Systems

ENABLE
Foundational Capabilities

- Avionics & Sensors
- Robotics & Autonomy
- Advanced Materials, Structures & Manufacturing
- Advanced Power & Thermal

- Capability Portfolio

CATALYSTS
Innovative Mechanisms

- NIAC/CIF/ECI
- STRG
- PCC
- Tech Transfer
- SBIR/STTR
- Flight Opportunities
- TP/ACO
- Inclusive Innovation

National Tech Base Priorities

Publicly-transparent, rigorously-developed process by which we establish our priorities based on comprehensive prioritized needs of our stakeholders

Idea Generation

OGAs

Industry

Academia

EOP

Hill

Mission Directorates

Centers

Investments/Projects

Mission Directorates

Centers

Industry

Academia

EOP

Hill

OGAs

Prioritized Shortfalls (Gaps)

Prioritized Shortfalls (Gaps)

Projects

Project 2	1525
Project 1	1219
Project 21	1213
Project 13	1135
Project 9	1101
Project 18	1050
Project 20	974
Project 11	535
Project 4	905
Project 24	836
Project 8	393
Project 23	757
Project 17	658
Project 16	601
Project 10	570
Project 15	568
Project 6	829
Project 5	523
Project 19	507
Project 14	490
Project 22	393
Project 3	340
Project 12	329
Project 7	225

$$$

Roadmaps

Initial Tech Status

Capability Goals

Integrated Top 30 Shortfalls Compared to Stakeholder Group Rank

Higher Ranking Shortfalls > Lower Ranking Shortfalls

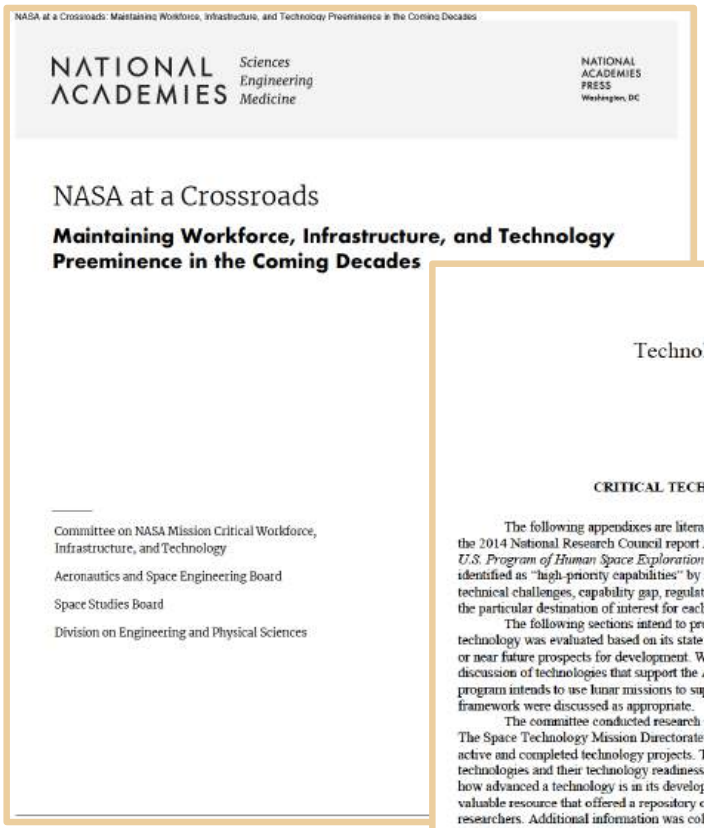
1 30 60 90 120 150 180

Not Ranked (NR)

Integrated Rank	Shortfall ID	Category	Stakeholder Group Rank								
			Academia	Small Industry	Large Industry	OGA	Other	NASA Centers	ESDMD	SMD	Other MDs
1	1618: Survive and operate through the lunar night	Thermal Management Systems	4	2	2	2	9	6	4	9	1
2	1596: High Power Energy Generation on Moon and Mars Surfaces	Power	13	1	1	40	20	4	21	NR	16
3	1554: High Performance Onboard Computing to Enable Increasingly Complex Operations	Avionics	80	28	21	27	13	3	34	1	56
4	1557: Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications	Communication and Navigation	9	11	15	29	67	10	28	NR	3
5	1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation	Autonomous Systems and Robotics	34	27	28	63	10	40	13	9	49
6	1552: Extreme Environment Avionics	Avionics	**176**	49	6	38	23	54	6	9	62
7	1519: Environmental Monitoring for Habitation	Advanced Habitation Systems	20	**101**	72	75	61	49	17	19	13
8	709: Nuclear Electric Propulsion for Human Exploration	Propulsion: Nuclear	43	**131**	23	4	52	32	7	NR	7
9	1304: Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility	Autonomous Systems & Robotics	27	42	30	**121**	**91**	34	25	25	66
10	1520: Fire Safety for Habitation	Advanced Habitation Systems	23	24	78	12	12	12	29	55	14
11	1531: Autonomous Guidance and Navigation for Deep Space Missions	Autonomous Systems & Robotics	47	67	24	3	89	42	64	23	15
12	1591: Power Management Systems for Long Duration Lunar and Martian Missions	Power	40	12	10	52	24	68	35	NR	27
13	702: Nuclear Thermal Propulsion for Human Exploration	Propulsion: Nuclear	36	**114**	36	14	78	62	7	NR	11
14	1559: Deep Space Autonomous Navigation	Communication and Navigation	62	**129**	27	5	**120**	38	64	23	10
15	1527: Radiation Countermeasures (Crew and Habitat)	Advanced Habitation Systems	5	23	22	6	2	5	63	NR	6
16	1526: Radiation Monitoring and Modeling (Crew and Habitat)	Advanced Habitation Systems	6	53	41	81	1	13	27	38	35
17	879: In-space and On-surface, Long-duration Storage of Cryogenic Propellant	Cryogenic Fluid Management	21	37	3	**95**	22	1	59	NR	2
18	1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions	Autonomous Systems & Robotics	42	17	26	**90**	16	44	14	26	57
19	1558: High-Rate Communications Across The Lunar Surface	Communication and Navigation	25	73	29	77	**162**	20	5	NR	51
20	1626: Advanced Sensor Components: Imaging	Sensors and Instruments	18	75	12	45	**160**	22	NR	18	68
21	792: In-space and On-surface Transfer of Cryogenic Fluids	Cryogenic Fluid Management	17	29	4	51	26	2	62	NR	29
22	1569: High-Mass Mars Entry and Descent Systems	Entry Descent and Landing	**152**	**156**	48	**117**	5	33	16	NR	12
23	1525: Food and Nutrition for Mars and Sustained Lunar	Advanced Habitation Systems	8	32	**116**	41	45	30	11	NR	58
24	1571: Navigation Sensors for Precision Landing	Entry Descent and Landing	14	62	37	23	4	31	45	28	9
25	1573: Terrain Mapping Capabilities for Precision Landing and Hazard Avoidance	Entry Descent and Landing	30	31	9	12	8	11	45	28	53
26	1562: Advanced Algorithms and Computing for Precision Landing	Entry Descent and Landing	54	65	45	23	3	25	45	28	8
27	1597: Power for Non-Solar-Illuminated Small Systems	Power	85	26	5	39	**125**	47	**93**	12	20
28	1568: Entry Modeling and Simulation for EDL Missions	Entry Descent and Landing	**101**	**115**	76	60	15	50	45	5	45
29	1516: Water and Dormancy Management for Habitation	Advanced Habitation Systems	49	**98**	**127**	**158**	53	69	26	51	22
30	1524: Crew Medical Care for Mars and Sustained Lunar	Advanced Habitation Systems	12	64	**94**	1	11	21	58	NR	17

ESDMD and SMD provided ranked lists (numbers shown above) in addition to shortfall scores (used for integrated list). ESDMD and SMD did not score all shortfalls. Unscored shortfalls were also not ranked.

Recent National Academy Review of NASA


NASA at a Crossroads: Maintaining Workforce, Infrastructure, and Technology Preeminence in the Coming Decades

NATIONAL ACADEMIES Sciences Engineering Medicine

NATIONAL ACADEMIES PRESS Washington, DC

NASA at a Crossroads

Maintaining Workforce, Infrastructure, and Technology Preeminence in the Coming Decades

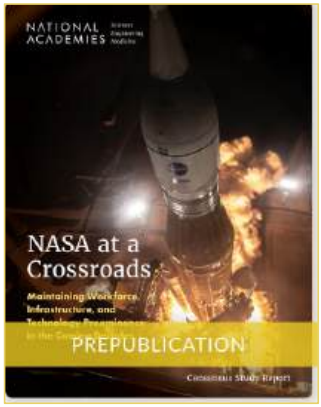
Committee on NASA Mission Critical Workforce, Infrastructure, and Technology

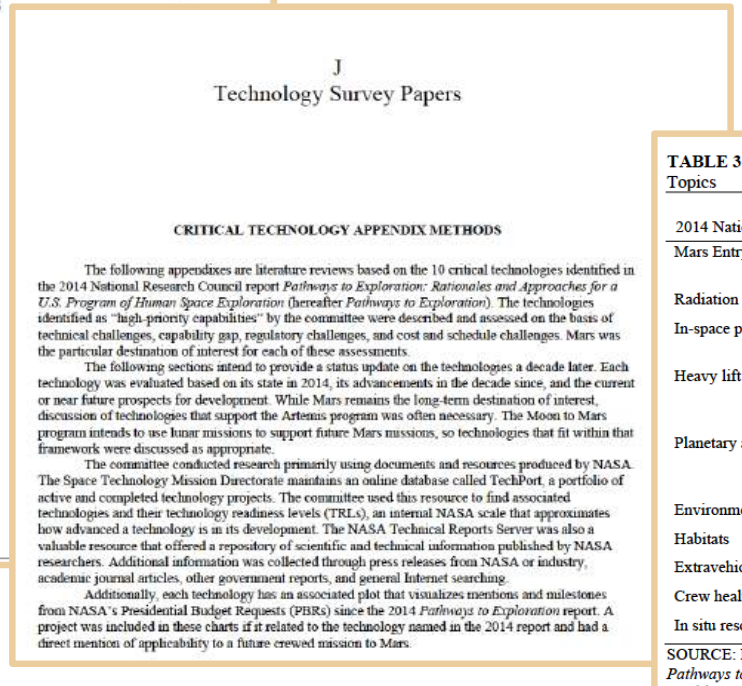
Aeronautics and Space Engineering Board

Space Studies Board

Division on Engineering and Physical Sciences

As the current Administrator of NASA has observed, "When we look at technology it is the essence of NASA."

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Technology Survey Papers

CRITICAL TECHNOLOGY APPENDIX METHODS

The following appendixes are literature reviews based on the 10 critical technologies identified in the 2014 National Research Council report *Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration* (hereafter *Pathways to Exploration*). The technologies identified as "high-priority capabilities" by the committee were described and assessed on the basis of technical challenges, capability gap, regulatory challenges, and cost and schedule challenges. Mars was the particular destination of interest for each of these assessments.

The following sections intend to provide a status update on the technologies a decade later. Each technology was evaluated based on its state in 2014, its advancements in the decade since, and the current or near future prospects for development. While Mars remains the long-term destination of interest, discussion of technologies that support the Artemis program was often necessary. The Moon to Mars program intends to use lunar missions to support future Mars missions, so technologies that fit within that framework were discussed as appropriate.

The committee conducted research primarily using documents and resources produced by NASA. The Space Technology Mission Directorate maintains an online database called TechPort, a portfolio of active and completed technology projects. The committee used this resource to find associated technologies and their technology readiness levels (TRLs), an internal NASA scale that approximates how advanced a technology is in its development. The NASA Technical Reports Server was also a valuable resource that offered a repository of scientific and technical information published by NASA researchers. Additional information was collected through press releases from NASA or industry, academic journal articles, other government reports, and general Internet searching.

Additionally, each technology has an associated plot that visualizes mentions and milestones from NASA's Presidential Budget Requests (PBRs) since the 2014 *Pathways to Exploration* report. A project was included in these charts if it related to the technology named in the 2014 report and had a direct mention of applicability to a future crewed mission to Mars.

TABLE 3-2 2014 National Research Council Report Versus 2024 Budget Breakdowns and Technology Topics

2014 National Research Council Report	2024 Budget Breakdown and Technology Topics
Mars Entry Descent and Landing (EDL)	Human Landing System Mars Entry, Descent, and Landing
Radiation safety	Crew health (radiation)
In-space propulsion and power	In-space Propulsion and Power Nuclear Propulsion
Heavy lift launch vehicles	Orion Space Launch Systems (SLS) Exploration Ground Systems
Planetary ascent propulsion	Gateway On-orbit Servicing Cryogenics
Environmental control and life support systems	Environmental control and life support
Habitats	Habitats
Extravehicular activity (EVA) suits	EVA, Suits and Human Surface Mobility
Crew health	Crew health (in-space)
In situ resource utilization (ISRU) (Mars atmosphere)	ISRU (gas and solids)

SOURCE: Based on data from Section 4.2.6.1, "High-Priority Capabilities," in National Research Council, 2014, *Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration*, Washington, DC: The National Academies Press, https://doi.org/10.17226/18801.

DEFENSE AND INTELLIGENCE

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- R&D opportunities as well as workforce development
- Space Force University Partnership Program
  - Georgia Institute of Technology
    Howard University
    Massachusetts Institute of Technology
    North Carolina Agricultural and Technical State University
    Purdue University
    University of Texas System (beginning with Austin and El Paso)
    University of Southern California
- On-campus classified facilities?
- Faculty interested in obtaining clearances?
- Students interested in obtaining clearances?
  - VaTech
  - GaTech
  - Univ of Arizona

SDA
SPACE DEVELOPMENT AGENCY

UNITED STATES
SPACE FORCE

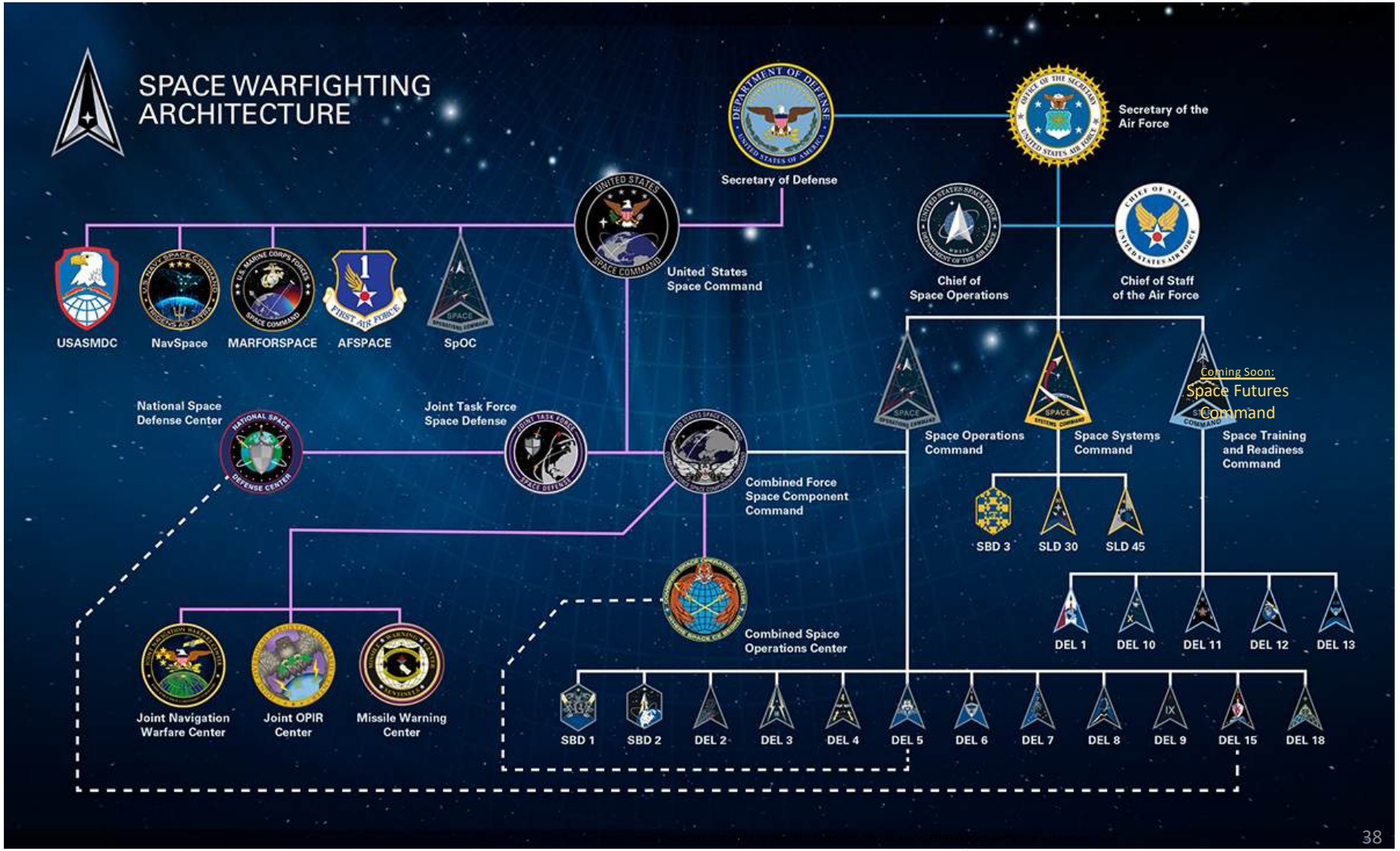
SPACE
DEFENSE
INNOVATION UNIT

NATIONAL RECONNAISSANCE OFFICE
UNITED STATES OF AMERICA

SPACEWERX

AIR FORCE RESEARCH LABORATORY

DARPA
DEFENSE ADVANCED
RESEARCH PROJECTS AGENCY


SPACE WARFIGHTING ARCHITECTURE
Secretary of Defense
Secretary of the Air Force
United States Space Command
Chief of Space Operations
Chief of Staff of the Air Force
USASMDC
NavSpace
MARFORSPACE
AFSPACE
SpOC
Coming Soon:
Space Futures Command
National Space Defense Center
Joint Task Force Space Defense
Space Operations Command
Space Systems Command
Space Training and Readiness Command
Combined Force Space Component Command
SBD 3
SLD 30
SLD 45
Combined Space Operations Center
DEL 1
DEL 10
DEL 11
DEL 12
DEL 13
Joint Navigation Warfare Center
Joint OPIR Center
Missile Warning Center
SBD 1
SBD 2
DEL 2
DEL 3
DEL 4
DEL 5
DEL 6
DEL 7
DEL 8
DEL 9
DEL 15
DEL 18

Rewrite today's rules to move forward to tomorrow

Images: WSF-M, Roman Filter Wheel, Integrated Cockpit Sensing Technology

SUSTAINABLE PITT SPACE ENGAGEMENT!

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