Space Power in the Dark
(. . . and without lawyers)

Chuck Finley

NASA Ames Research Center

Agenda

Making a Case for Beamed Power

Candidate Vision for Space Solar Power

Space Solar State-of-the-Art

Cost of the Sun -- Bounding Constraints to Space Solar Power

Alternate Architecture for Beamed Space Power

Walking Away From and Back To Space Nuclear

Making a Case for Beamed Power
Does it make sense?

"Power can be, and at no distant date will be, transmitted without wires, for all commercial uses, such as the lighting of homes and the driving of aeroplanes. In years to come wireless lights will be as common on the farms as ordinary electric lights are nowadays in our cities."

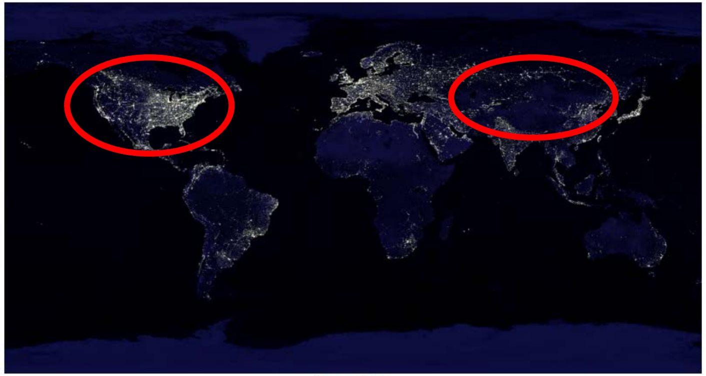
(Nikola Tesla, The American Magazine, April 1921)

Intra-domain

- Earth-to-Earth
- Space-to-Space
- Moon-to-Moon

Cross-domain

- Space-to-Moon
- Space-to-Earth



Source: NASA

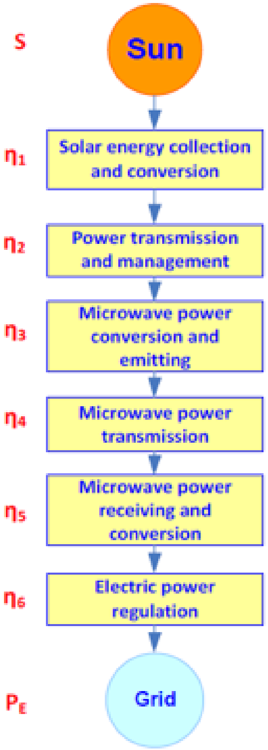
Many parts of the world remain in the dark.

Candidate Vision for Space Solar Power

Recent SPS Activities in China

Nxinbin Hou, Li Wang; Qian Xuesen Laboratory of Space Technology

Efficiency Chain



System Efficiency

Factors	Efficiency	System efficiency
Solar energy collection and conversion（0.29）		
Solar cell	0.40	**0.4**
Error of Sun-pointing	0.99	**0.396**
Gap of solar cells	0.85	**0.336**
Angle of sunlight	0.958	**0.322**
Space environment effect(EOL)	0.90	**0.290**
Power transmission and management（0.849）		
Voltage conversion in solar array	0.95	**0.276**
Transmission	0.95	**0.262**
Voltage conversion in antenna	0.95	**0.249**
Consumed by service devices	0.99	**0.246**
Microwave power conversion and emitting（0.7125）		
Microwave generator	**0.75**	**0.185**
Microwave regulation	0.95	**0.176**
Microwave power transmission		
Microwave transmission	**0.095**	**0.0217**
Microwave power receiving and conversion（0.72）		
Receiving antenna	0.9	**0.0167**
Rectifier circuits	**0.8**	**0.0133**
Electric power regulation（0.97）		
Electric power collection	0.98	**0.0130**
Voltage conversion	0.99	**0.0129**

Recent SPS Activities in China

Nxinbin Hou, Li Wang; Qian Xuesen Laboratory of Space Technology

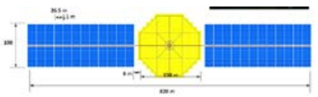
Orbit	GEO
Delivered power	~1MW
Size	~150m(X)×820m(Y)×100m(Z)
Total mass	~300t
Solar cell	Thin-film GaAs
Efficiency	~40%
Output power	~24MW
Voltage of solar array modules	~500V
Mass	~60t
Frequency of microwave	5.8GHz
Diameter of transmitting antenna	~150m
Beam precision	0.003°
Diameter of receiving antenna	~5km
Mass	~100t
Voltage of main cable	5000 V
Number of rotary joints	24
Mass	~65t
Module	Deployed truss
Mass	~40t
Thrusters	20kW electric thruster
Mass	~20t
Mass of thermal Management	~10t
Mass of ISRM	~5t
Continuous transmission	

Orbit	GEO
Delivered power	~1GW
Efficiency	~13%
Total mass	~10000t
Solar cell	Thin-film GaAs
Efficiency	~40%
Area of solar array	~6km^2
Output power	~2.4GW
Voltage of solar array modules	~500V
Mass	~2000t
Frequency of microwave	5.8GHz
Efficiency	~54%
Diameter of transmitting antenna	1000m
Number of antenna modules	128000
Transmitting power of an antenna module	12.5 kW
Mass	4000t
Diameter of receiving antenna	5km
Style	Mix of distributed and centralized
Voltage of main cable	20 kV
Voltage of solar sub-arrays	5000 V
Number of rotary joints	100
Mass	2500t
Module	Deployed truss
Mass	1200t
Thrusters	1N electric thruster
Mass	100t
Mass of thermal Management	150t
Mass of ISRM	50t
Continuous transmission	

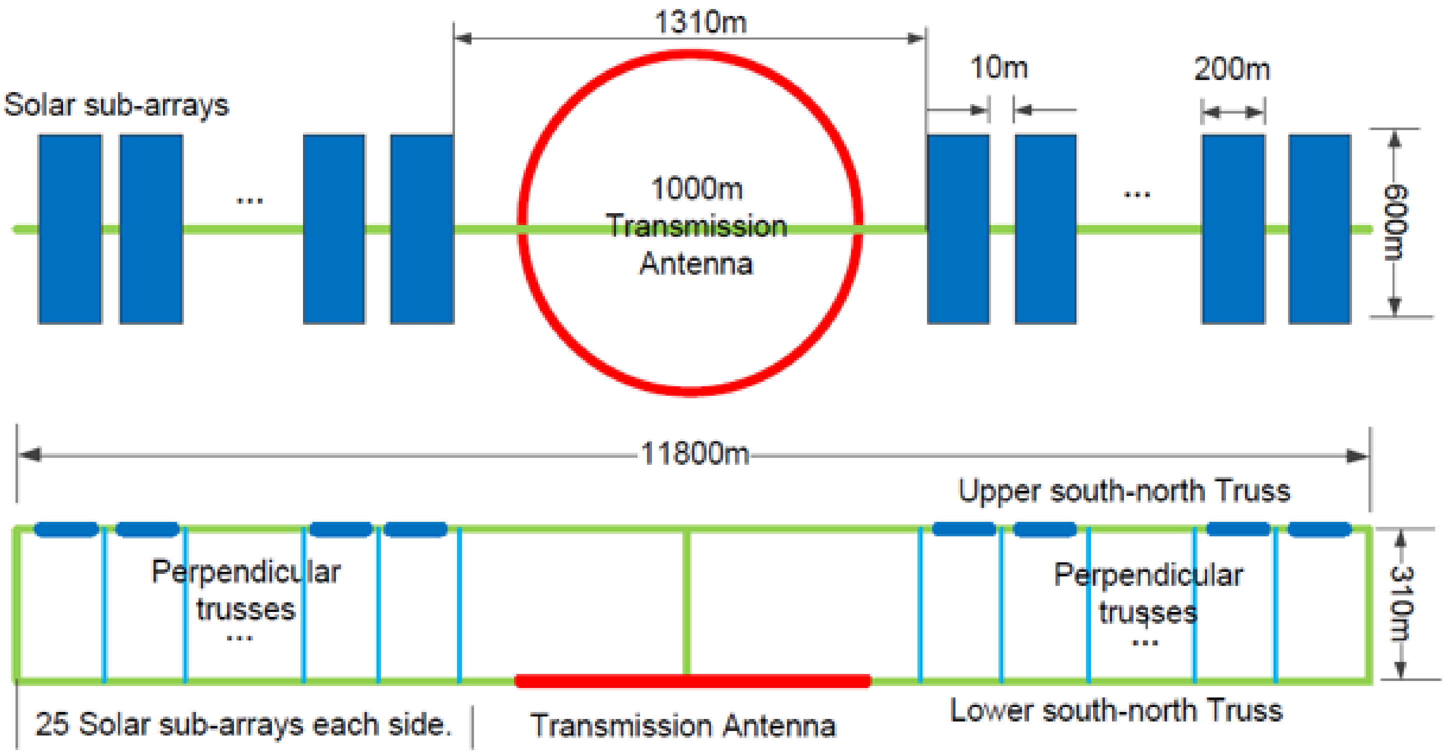
Recent SPS Activities in China

Nxinbin Hou, Li Wang; Qian Xuesen Laboratory of Space Technology

Configuration(1MW)



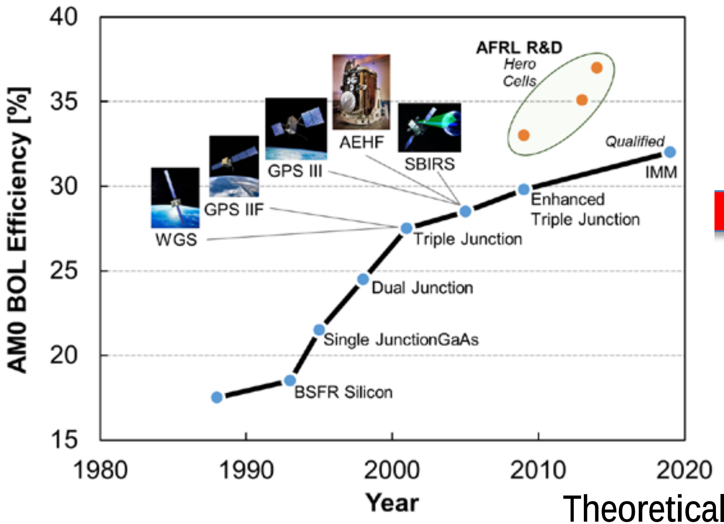
Configuration(1GW)

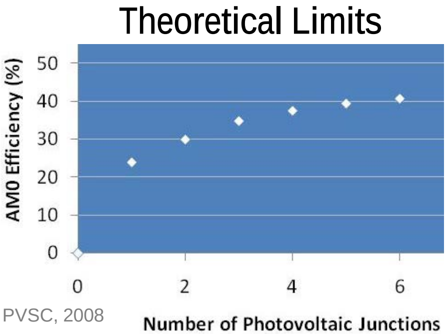


Space Solar State-of-the Art

Dr Kyle Montgomery, Advanced Space Power, AFRL/RV

Where We Have Been – Space Solar Cells





Source: P. Sharps, 33rd IEEE PVSC, 2008

Shift Towards Enabling *New Capabilities*

Credit: https://www.wired.com/2014/03/space-solar/

Credit: http://environment.umn.edu/discovery/game-changing-research/

Credit: https://spacenews.com/op-ed-the-move-from-survivability-to-resilience/

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Ben Franklin's famous kite experiment

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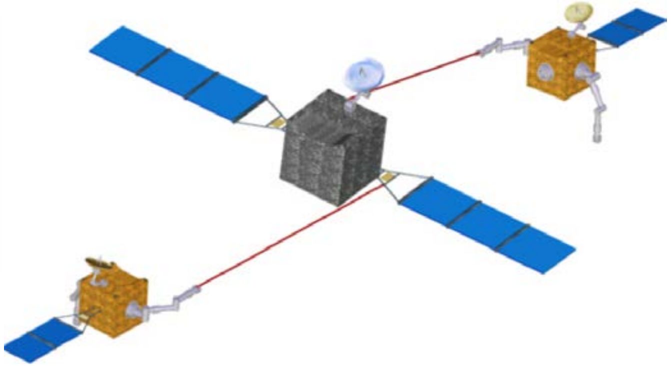
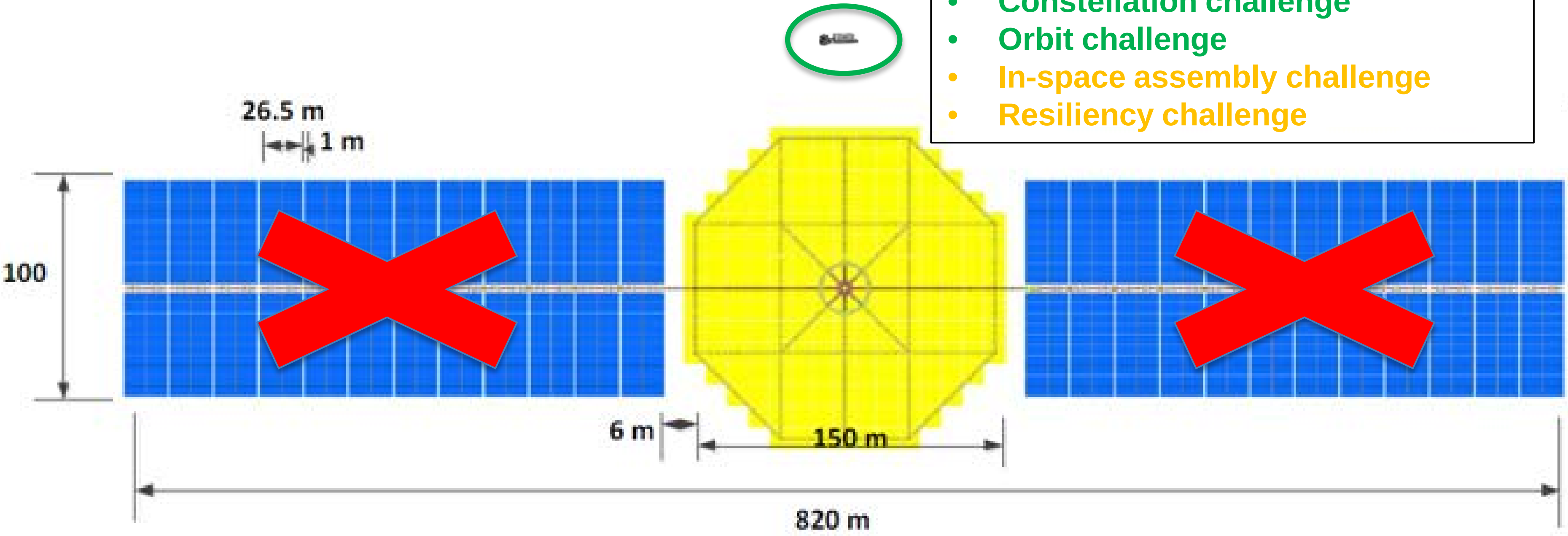


Alternate Architecture for Beamed Space Power

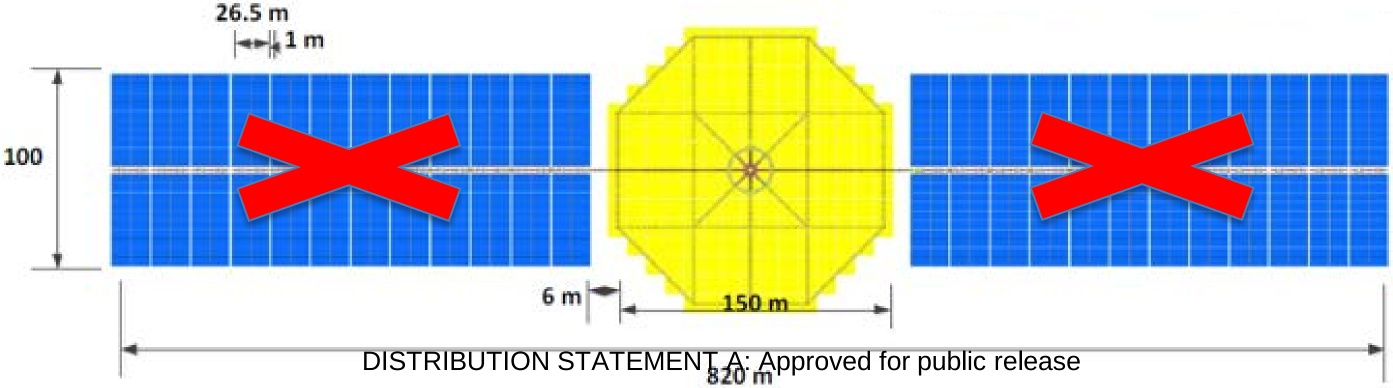
1MW Configuration

- Collection aperture size challenge
- Constellation challenge
- Orbit challenge
- In-space assembly challenge
- Resiliency challenge



The US Military Wants Tiny Road Mobile Nuclear Reactors

Joseph Trevithick



Walking Away From Space Nuclear

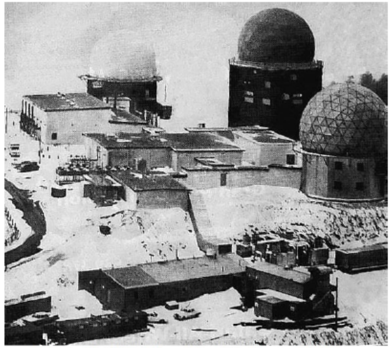
Jeff Waksman, Strategic Capabilities Office

Portable Nuclear Power: An Old Idea

- **The U.S. Army Nuclear Power Program ran from 1954 through 1977.**
  - Eight reactors were constructed (five were portable), each between 1-10 MWe, of various designs and for various purposes.

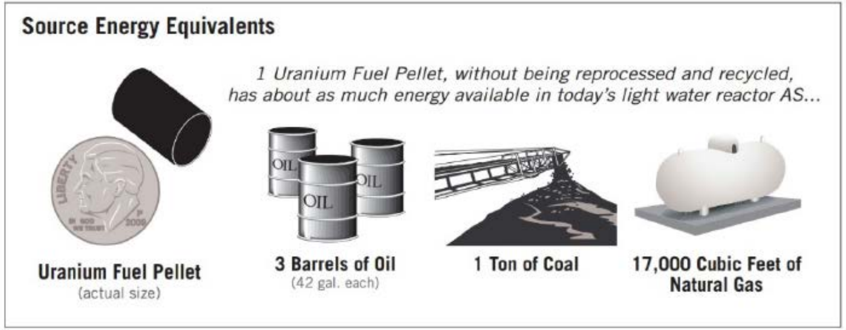
- **The first U.S. nuclear reactor to be connected to an electrical grid, in 1957, was an Army reactor (SM-1).**

- **As some of the earliest nuclear reactors ever built, they were technologically difficult to operate, unreliable, and too expensive relative to abundant fossil fuel alternatives.**



PM-1 Nuclear Plant (PWR), Sundance Air Force Station, Wyoming, 1962-1968

ML-1 US Army reactor, 1958, Arco, Idaho



Walking Back To Space Nuclear – Project Pele

Jeff Waksman, Strategic Capabilities Office

Small Nuclear Reactors Are Already Here

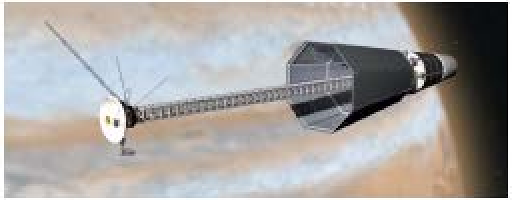
- **2019 NDAA requires a DoE/DOD plan to achieve the operation of a small nuclear reactor at a DOD installation no later than 2027.**
- **USD(R&E) Michael Griffin has assigned the task of developing a mobile nuclear reactor to the Strategic Capabilities Office (SCO).**

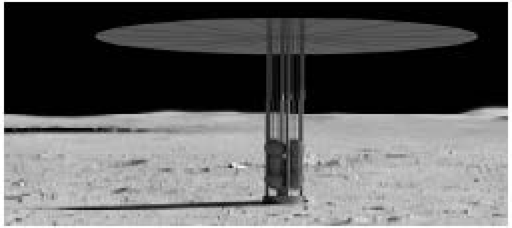
Walking Back To Space Nuclear -- Kilopower

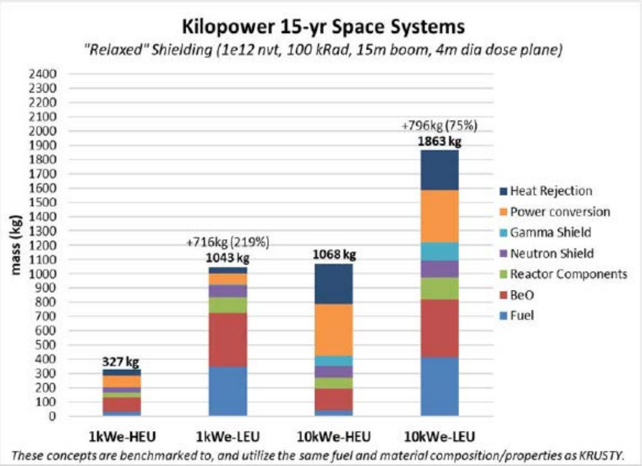
Max Chaiken, NASA Glenn Research Center

From the NASA FY2020 Budget Proposal

The Lunar Surface Innovation Initiative activities will be implemented through a combination of in-house activities, competitive programs, and public-private partnerships. The Initiative will bring together the full range of stakeholders, including entrepreneurs, academia, small businesses, industry and the NASA workforce to catalyze technology development. For example, this Initiative will develop and integrate systems used for in situ resource utilization and processing into mission consumables, including oxygen, water, and hydrogen. This capability will reduce mission mass, cost, and risk of human exploration, and increase independence from the Earth's resources. ***NASA's Kilopower technology will transition into a demonstration mission - building on the 2018 demonstration of a small, lightweight nuclear fission power system that would permit long duration crewed missions on the surface of the Moon.*** Furthermore, the Initiative will jumpstart fuel cell development, space weather monitoring, and improve systems and components to allow survival and operation through the cold lunar night.

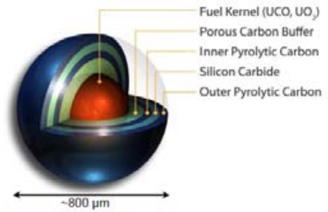






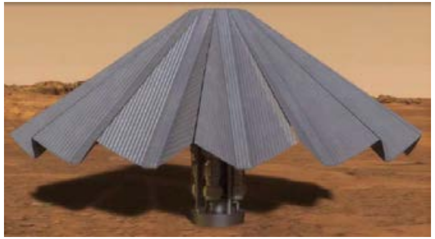
Space Nuclear State of the Art

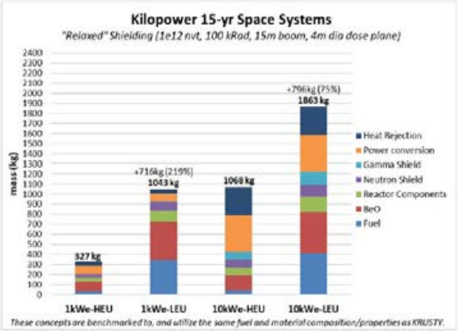
SCO Project Pele



Tristructural isotropic (TRISO) particle

NASA Kilopower





- **Design → Terrestrial (2023) → Space**
- **1 → 10MWe**
- **<40tons (primarily shielding) → ??**
- **HEU → HALEU TRISO fuel**
- **Power in 2023**

- **Ground demo 2018 → Space demo ??**
- **1 → 10kWe**
- **EM electronics → Space-qualified**
- **HEU U235 fuel → ??**
- **Earth power in 2018**

DISCUSSION

Hybrid High Ground

Lunar/Cislunar Domain Awareness/Control

CHUCK FINLEY, SPACE EXPERIMENTS AND PROGRAMS PORTFOLIO LEAD

AFRL/RVEP, 11 June 2019

Topics

- Recipe for a contested domain
- Hybrid Architecture
- Prepping the “battlefield”
- Opportunistic Layer
- Intentional/Conditional Layers

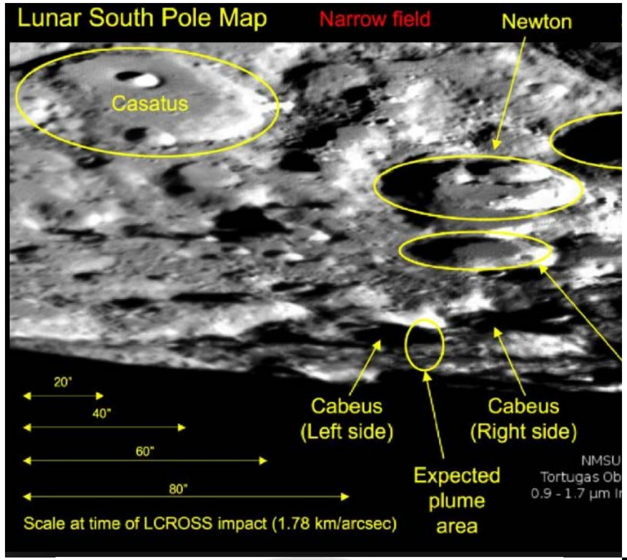
Recipe for a Contested Domain

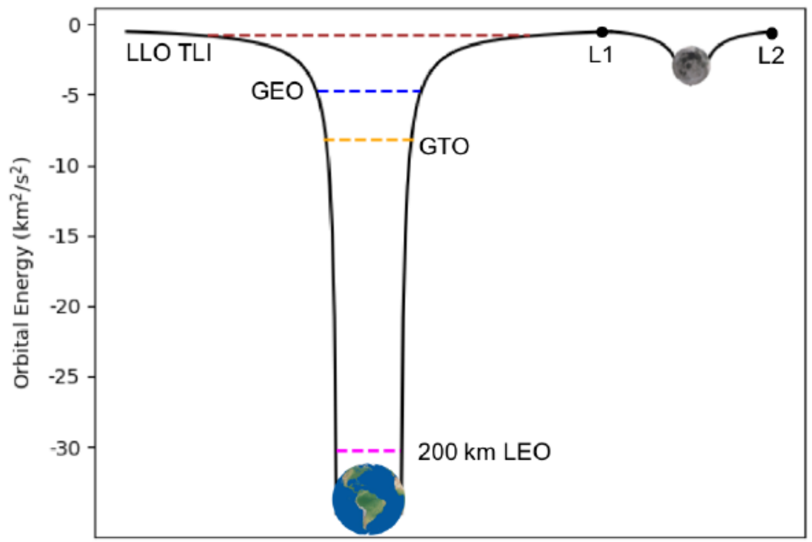
History of the American West

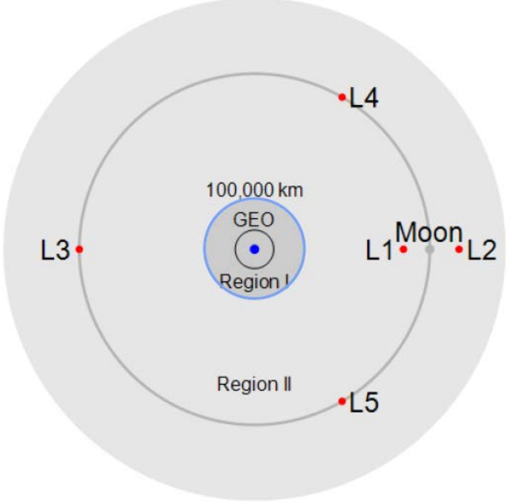
- First explored > 12,000 years ago
- First "settled" > 700 years ago
- **1850 SITREP**
  - Increasingly acknowledged value
  - Raw
  - Contested
- **How did the US achieve "control" over its adversaries?**
  - Superior awareness
  - Superior communications, "precision" navigation and timing
  - Superior logistics
  - Control of power generation and distribution

History of the Moon

- "Launched" from Earth > 4 billion years ago
- "Spaceship Moon" contains the following harvestable resources:
  - Real estate, sub-surface shelter, gravity, water, oxygen, solar energy, no atmospheric interference or drag, TBD "other"
  - Gravitational proximity to Earth GEO
  - "Hiding places" on tidally locked far side and L2
- **2019 SITREP**
  - Increasingly acknowledged value
    - Civil
    - Commercial
  - Raw
  - **Contested?**

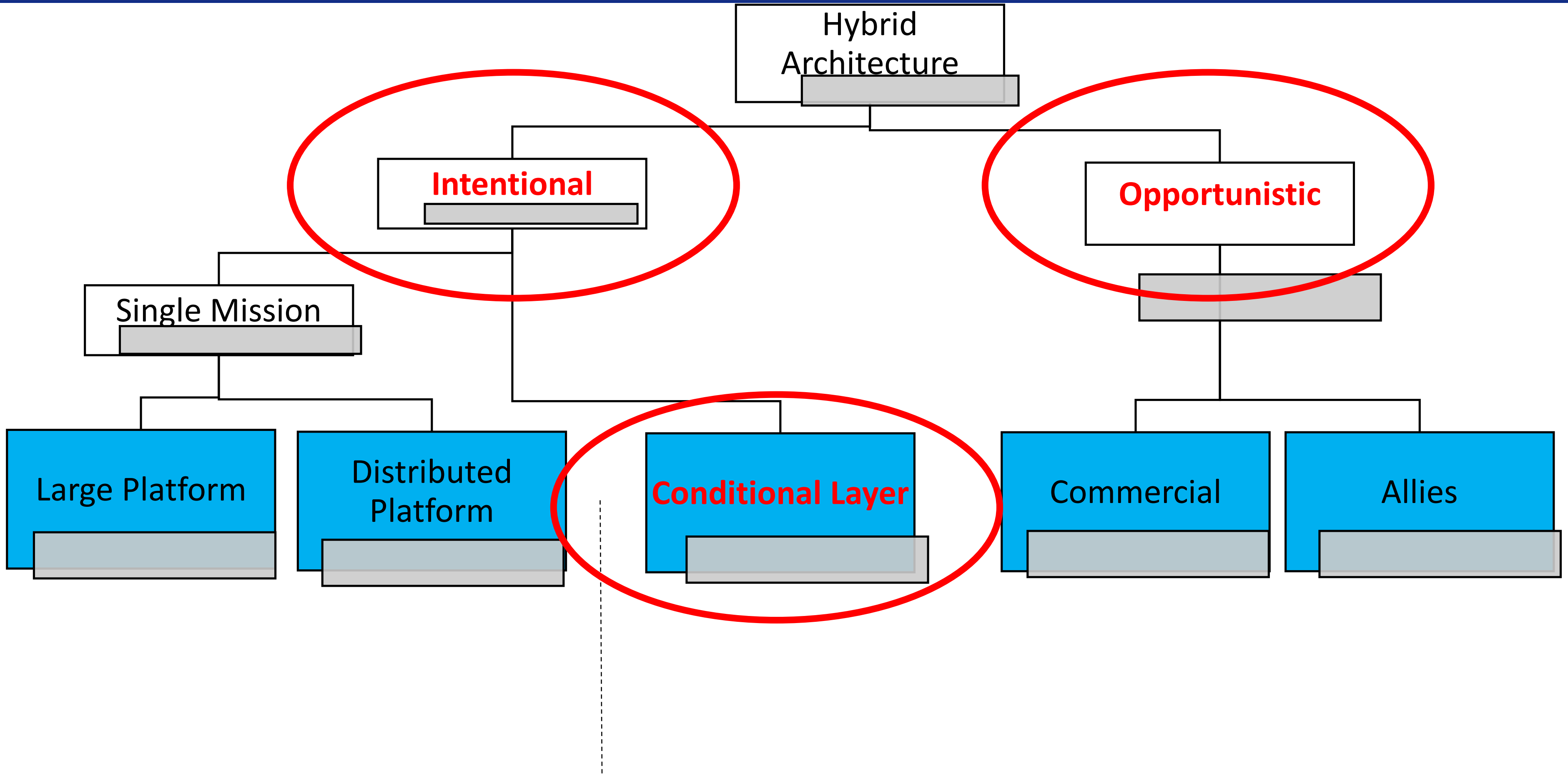






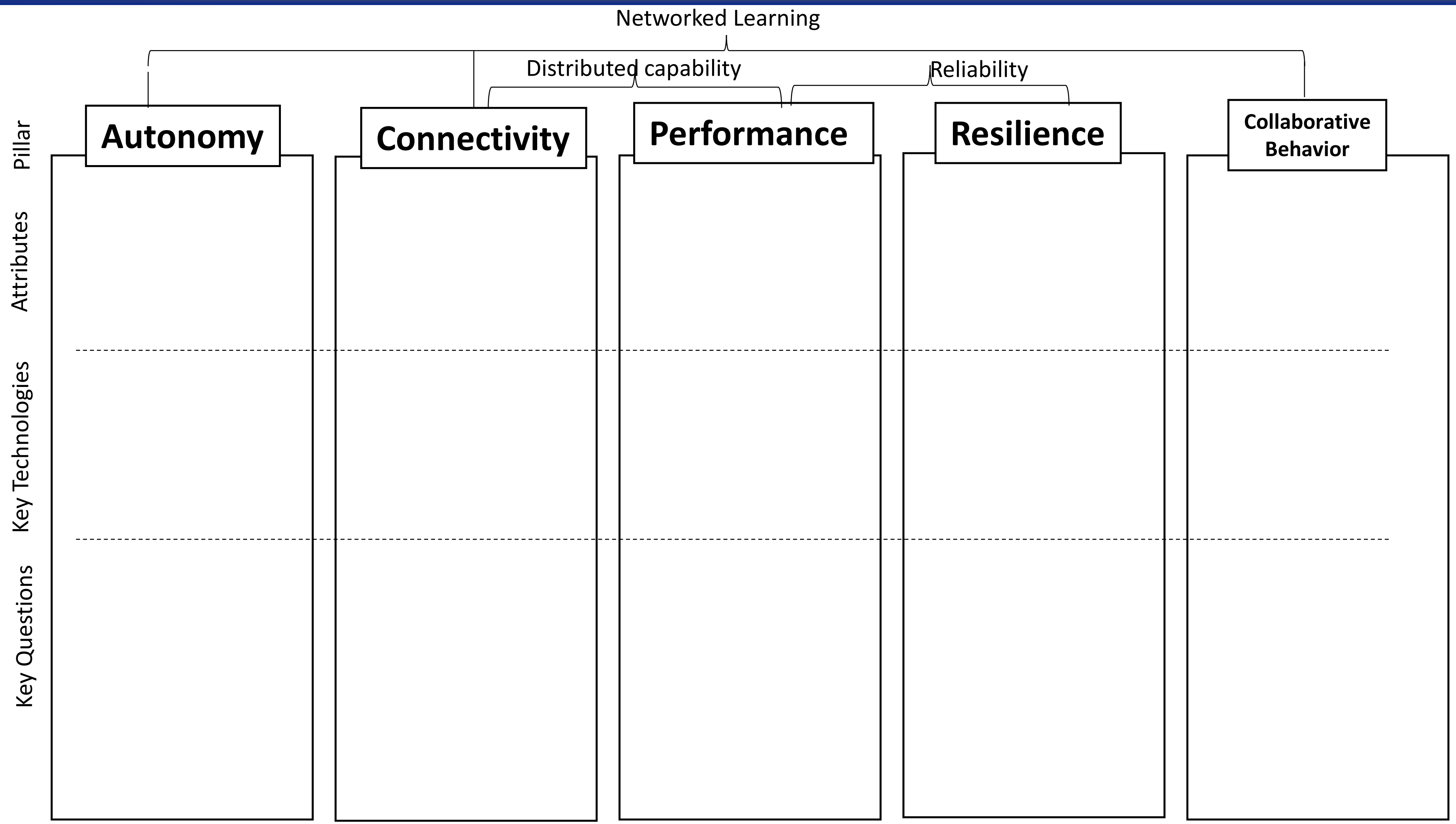
Hybrid Architecture

Layers of the Hybrid Architecture

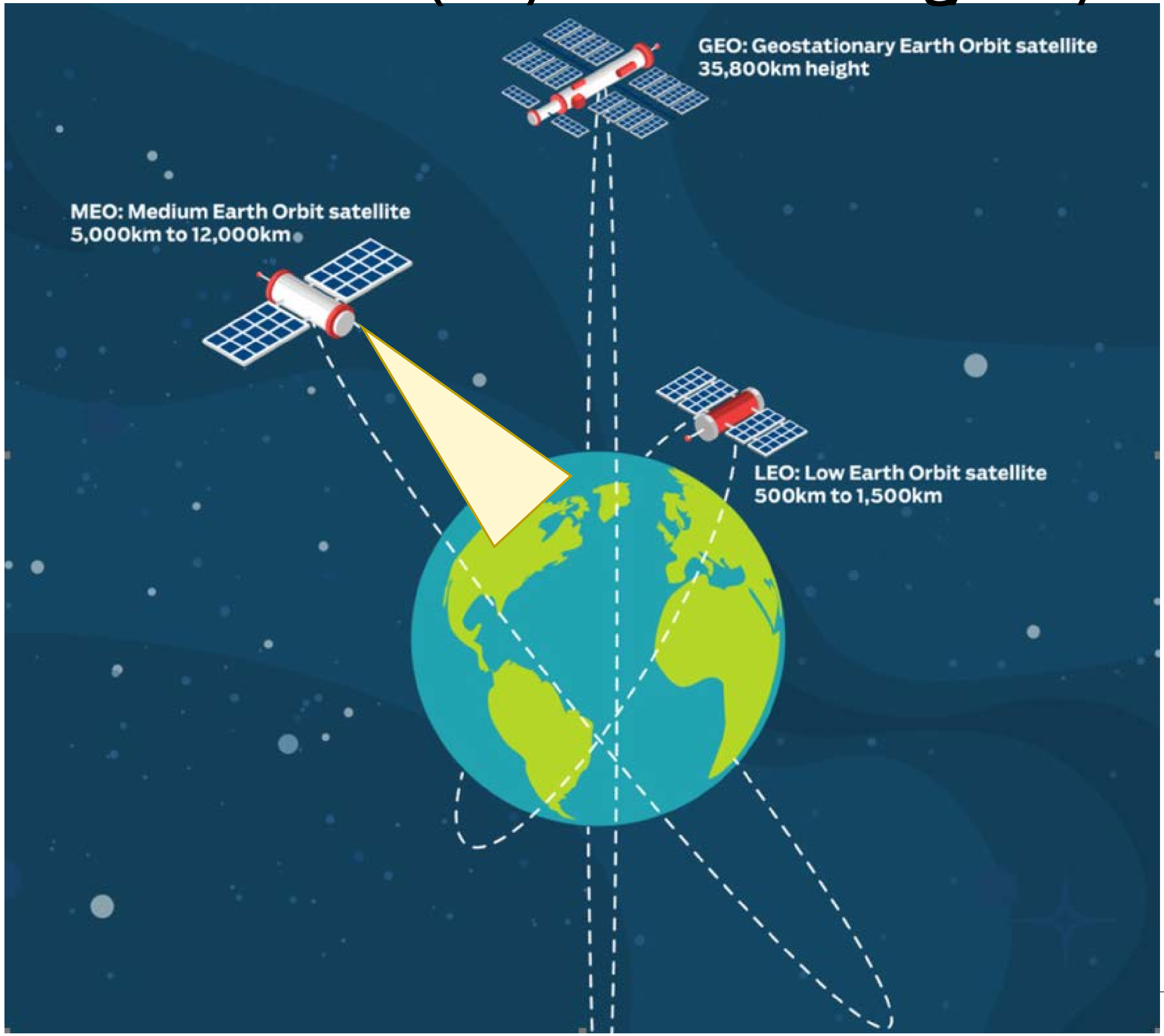


It is critical we know end-state deployment strategy as it will drive the requirements of the system or technology we develop

Pillars of Distributed Satellite Systems



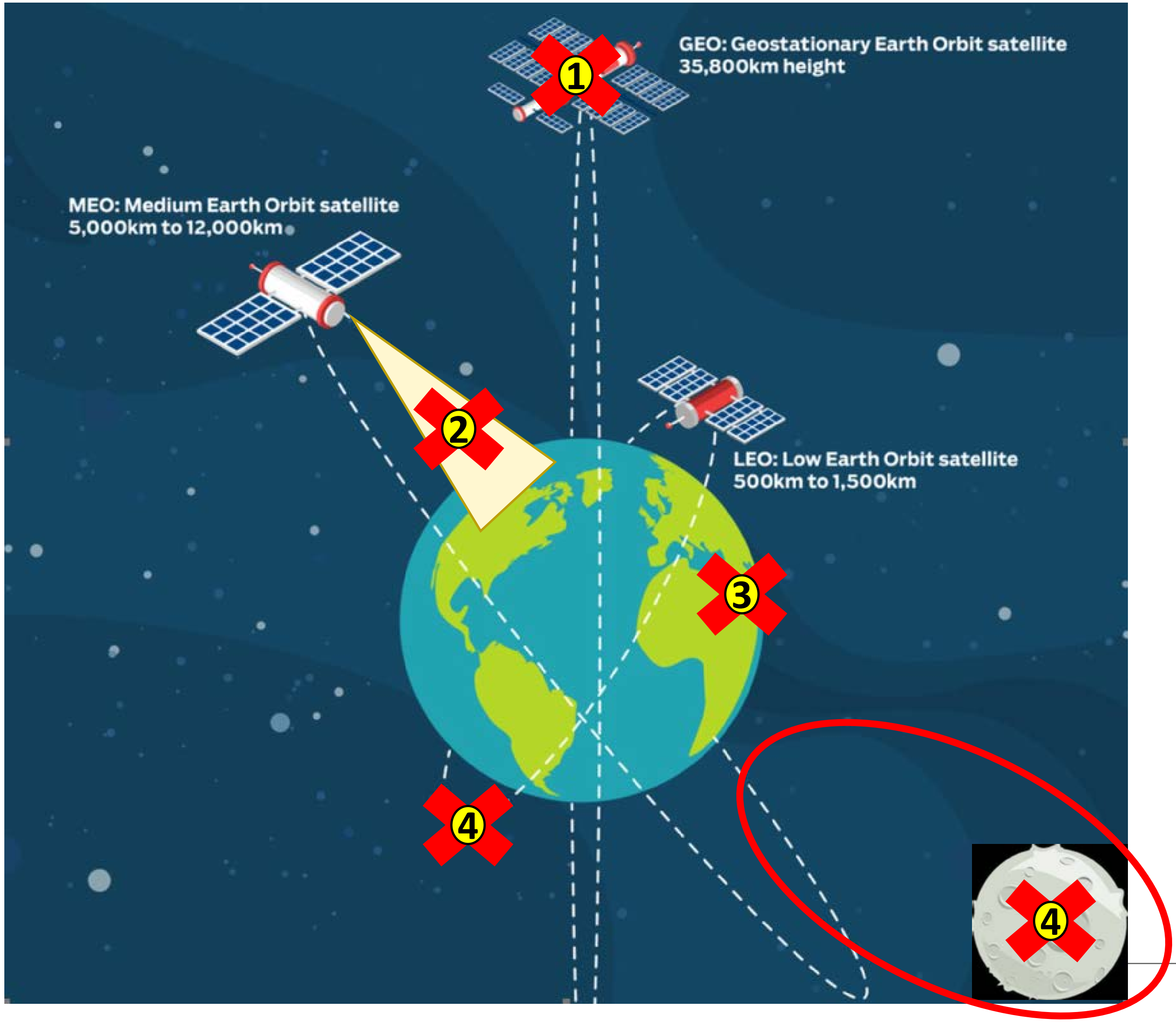
Historical Objective: Strategically Persistent Space Effects (ISR/Missile Warning/PNT/Comm/Weather/SSA)



Objective: Exquisite capability in all space mission areas in all Areas of Interest (AOIs) against all adversaries all the time.

AFRL

Modern Threshold: “Fight Through Solutions for a Contested Domain”



~~**Objective:** Exquisite capability in all space mission areas in all areas of interest (AOIs) against all adversaries all the time.~~

- Contested:

1. Space Systems
2. Space Signals
3. Space Military Effectiveness
4. Space Domain

Threshold: Fight-through resilience of critical space effects in critical AOIs for critical time periods despite contesting adversaries.

Prepping the "battlefield"

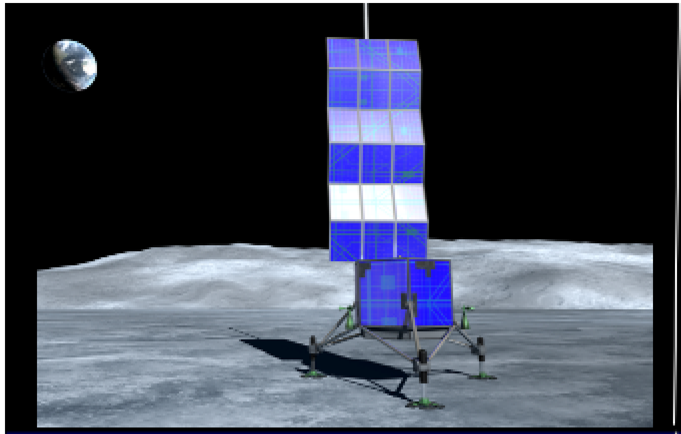
Hybrid High Ground -- 1850 American West "Do Over"

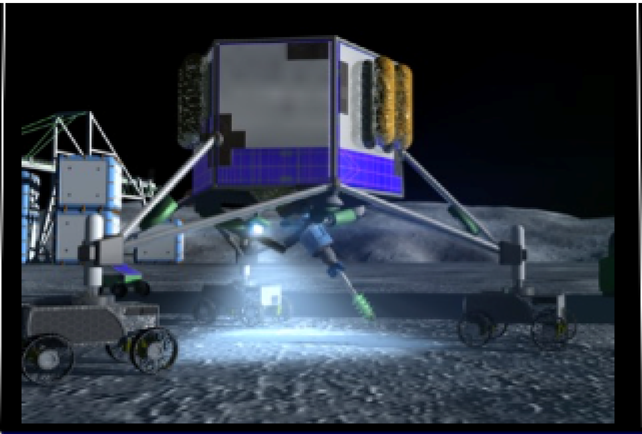
- **How should the US achieve "control" over its Domain?**
  - **Superior awareness**
    - Surface or overhead or cross-domain sensors?
    - Remote or proximity ops systems?
    - South pole or far side or L2 or L1 or . . . ?
  - **Superior communications, "precision" navigation and timing**
    - Surface or overhead or cross-domain sensors?
    - RF or optical sensors?
  - **Superior logistics**
    - Digital or material?
  - **Control of power generation and distribution**
    - Solar or nuclear source?
    - Wires or wireless distribution?

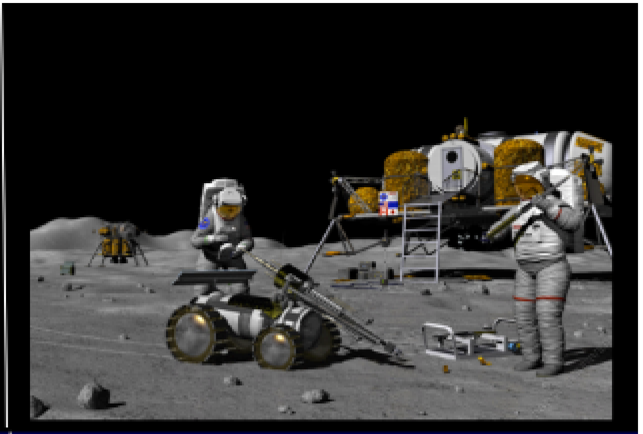
BACKUP

Opportunistic Layer

NASA Commercial Lunar Payload Services (CLPS)







Phase 1: Fast, Low-Cost, Commercial-Enabled Missions

- Partner with industry to develop and demonstrate capabilities to enable an evolvable lunar infrastructure, including:
  - Lunar cargo delivery, mobile power stations, communication towers and satellites, lunar surface rovers, etc
- Obtain ground truth data at several lunar sites:
  - Identify resources and hazards
  - Determine economic viability for resource extraction.

Phase 2: Pilot Scale Demonstration

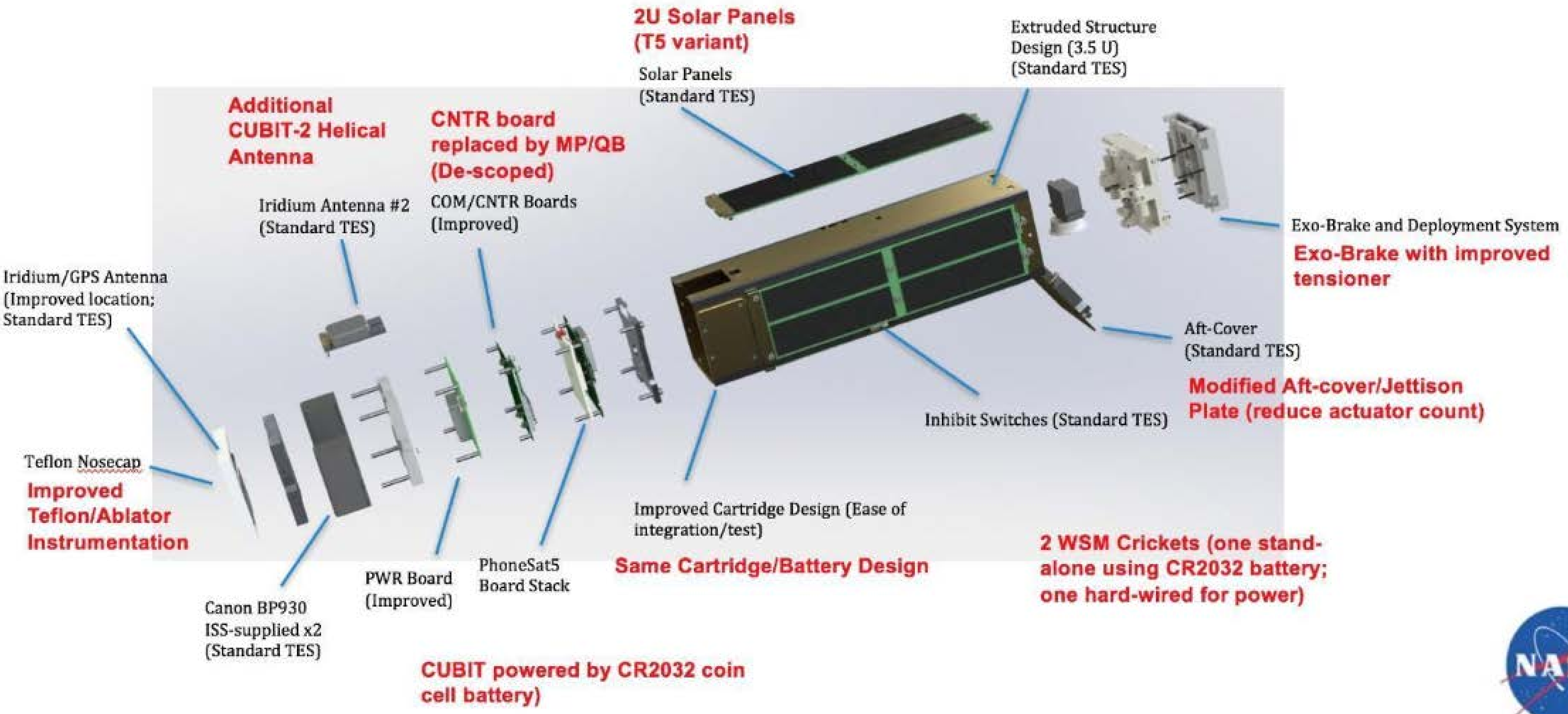
- Demonstrate multipurpose infrastructure services on a pilot-scale to support future NASA crew missions and commercial activities, such as, lunar mining.
- Develop a pilot-scale ISRU plant to extract water and produce up to 1 metric ton of propellant.
- Evaluate feasibility and economics of scaling up production to full scale.

Phase 3: Long-Term Contracts

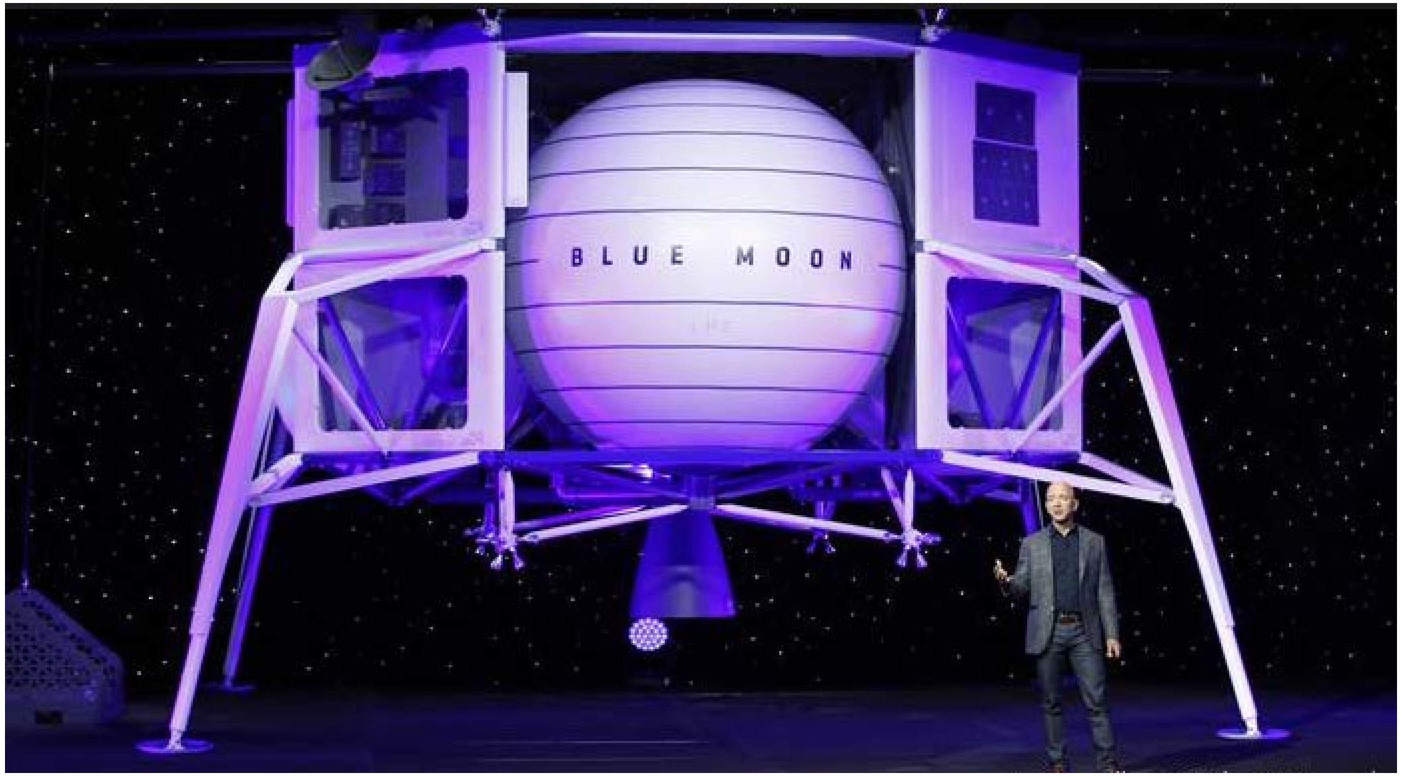
- NASA awards long-term contracts for infrastructure services, such as, lunar cargo delivery and power/comm services to support human missions.
- NASA may also award long-term contracts for full-scale resource extraction and/or delivery of resources to cis-lunar destinations.

NASA Space Communications and Navigation (SCaN) Program

NASA Small Sample Return

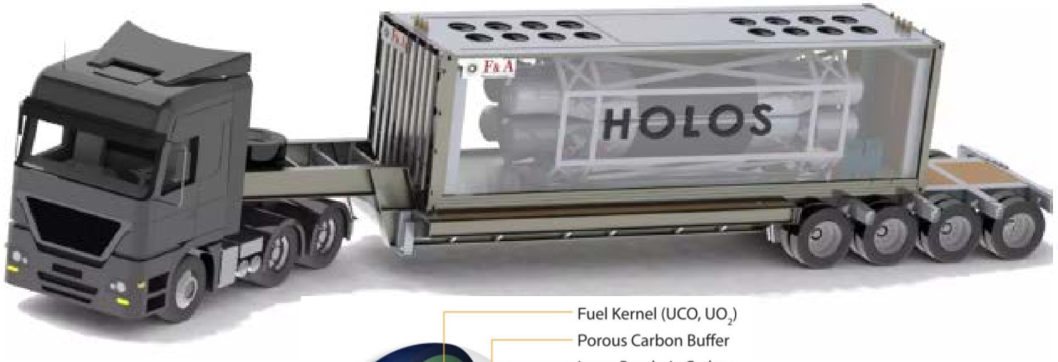


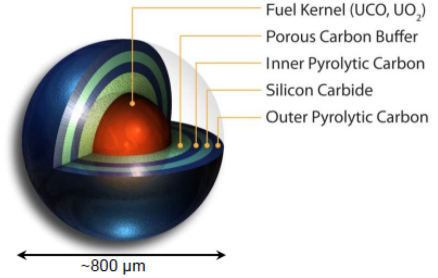
Amazon Digital and Material Logistics Chain



Tactical Power Generation

SCO Project Pele





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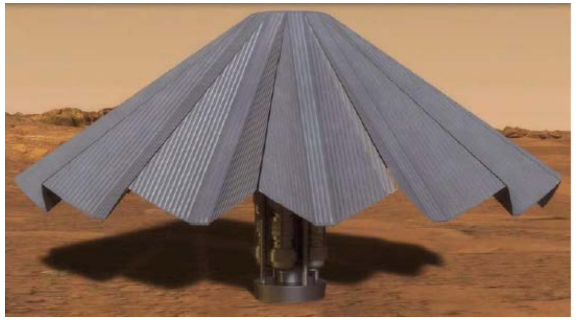

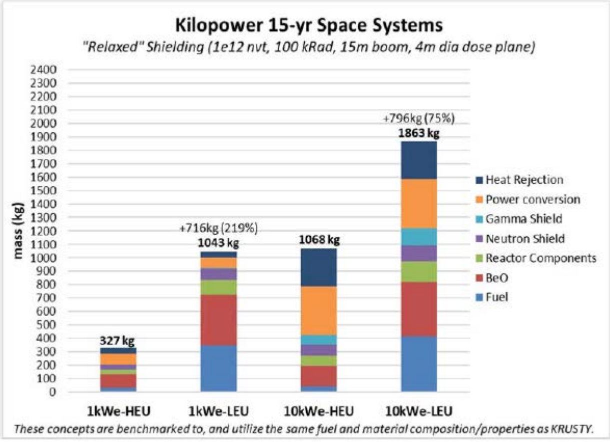

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