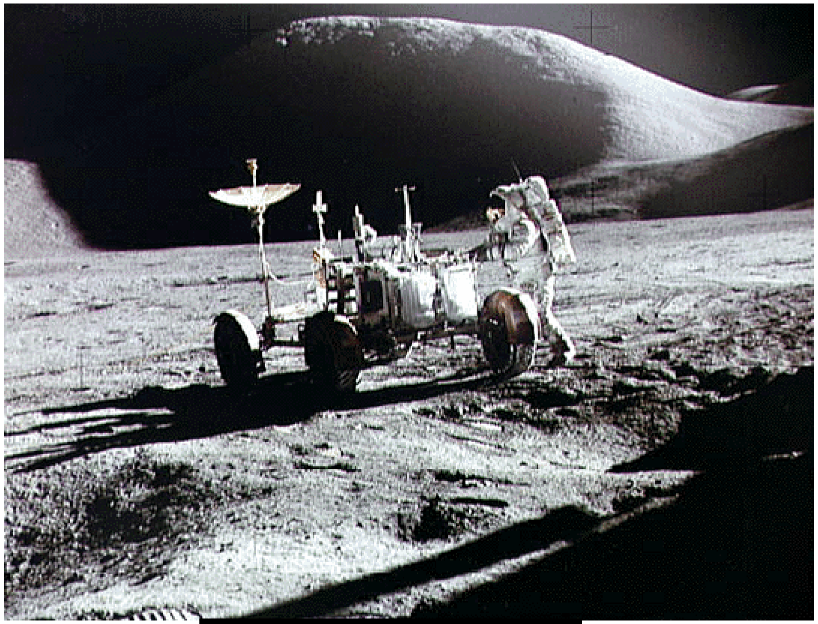


From Value to Architecture:

The Exploration System of Systems

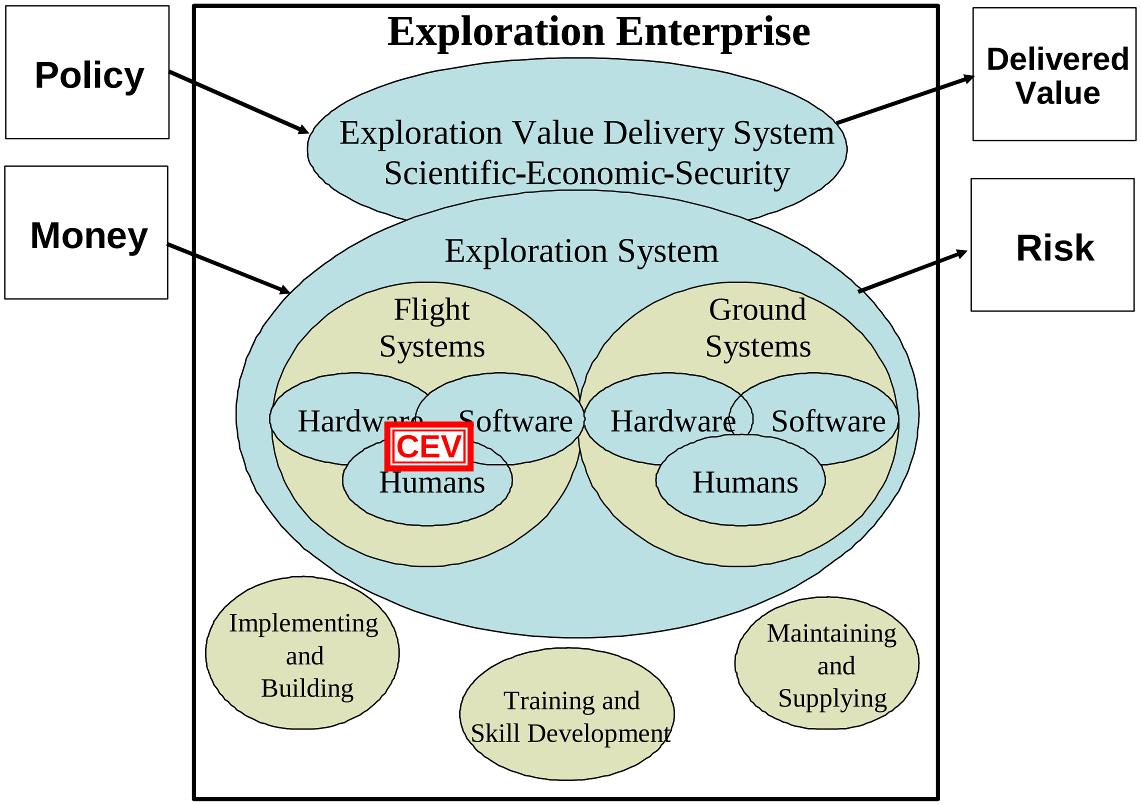
MIT

Dec. 1, 2004

Sustainability

- Our goal is to help NASA identify *sustainable* system of system architectures for exploration
- Sustainability requires *value delivery*, *affordability*, *risk management* and *policy robustness*
- Our approach is to:
  - Define measures of sustainability for design
  - Comprehensively search the architectural space(s)
  - Identify key policy, technology and operational decision branches
  - For each decision branch, optimize the system
  - Project the resulting functionality onto the CEV, to determine the robustness of its requirements to further downstream decisions
  - Identify the benefit of certain decision branches

A Holistic View: the Sustainable System



Policy

Money

Exploration Enterprise

Exploration Value Delivery System
Scientific-Economic-Security

Exploration System

Flight Systems

Hardware

Software

CEV

Humans

Ground Systems

Hardware

Software

Humans

Implementing and Building

Training and Skill Development

Maintaining and Supplying

Delivered Value

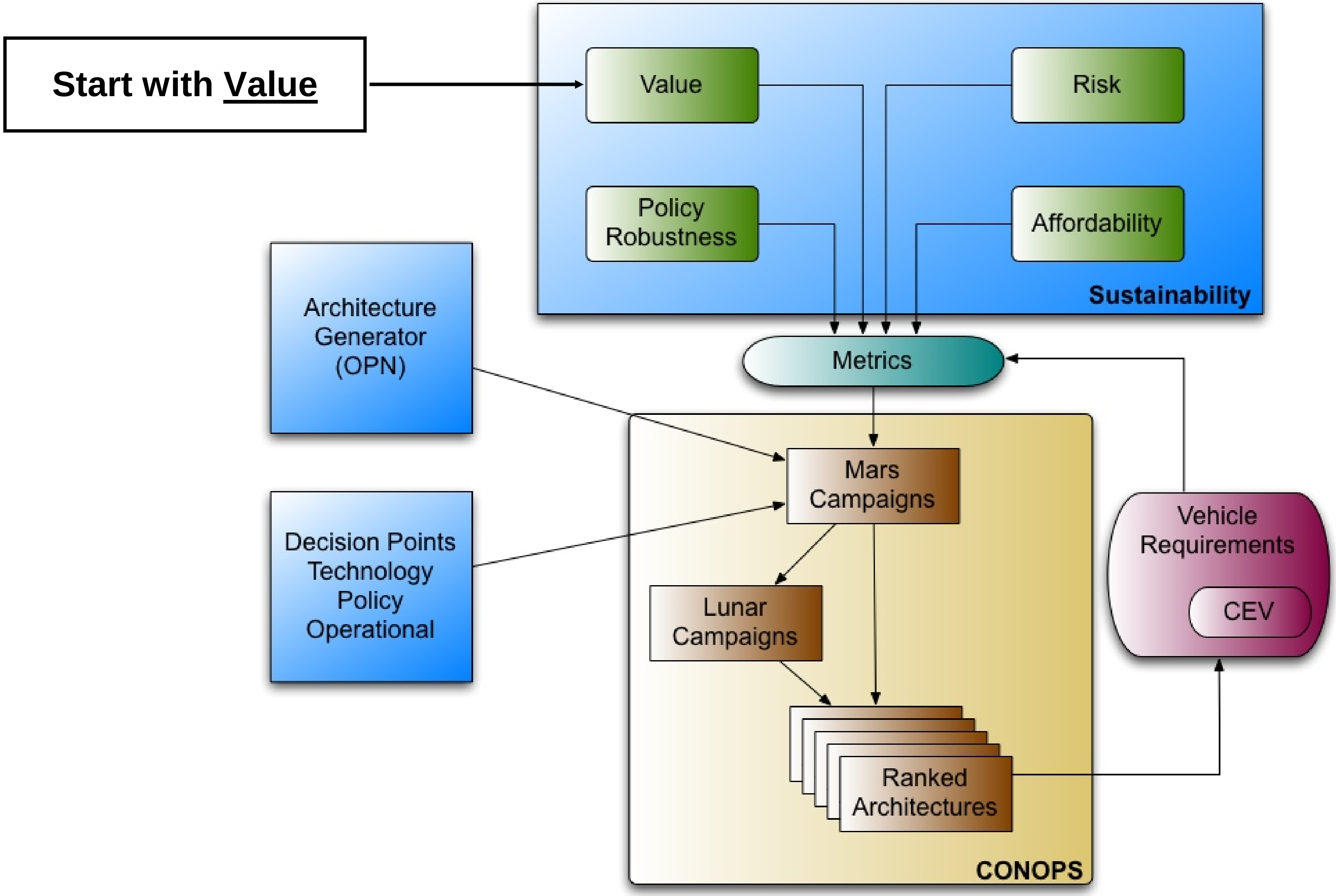
Risk

The sustainable system is this …

Not this

- A ***Holistic*** **view of the ground and flight elements, their development, operation and human capital, and the extended enterprise is necessary to ensure sustainability**

From Sustainability to Requirements



Start with Value

Value

Risk

Policy Robustness

Affordability

Sustainability

Metrics

Architecture Generator (OPN)

Decision Points
Technology
Policy
Operational

Mars Campaigns

Lunar Campaigns

Ranked Architectures

CONOPS

Vehicle Requirements

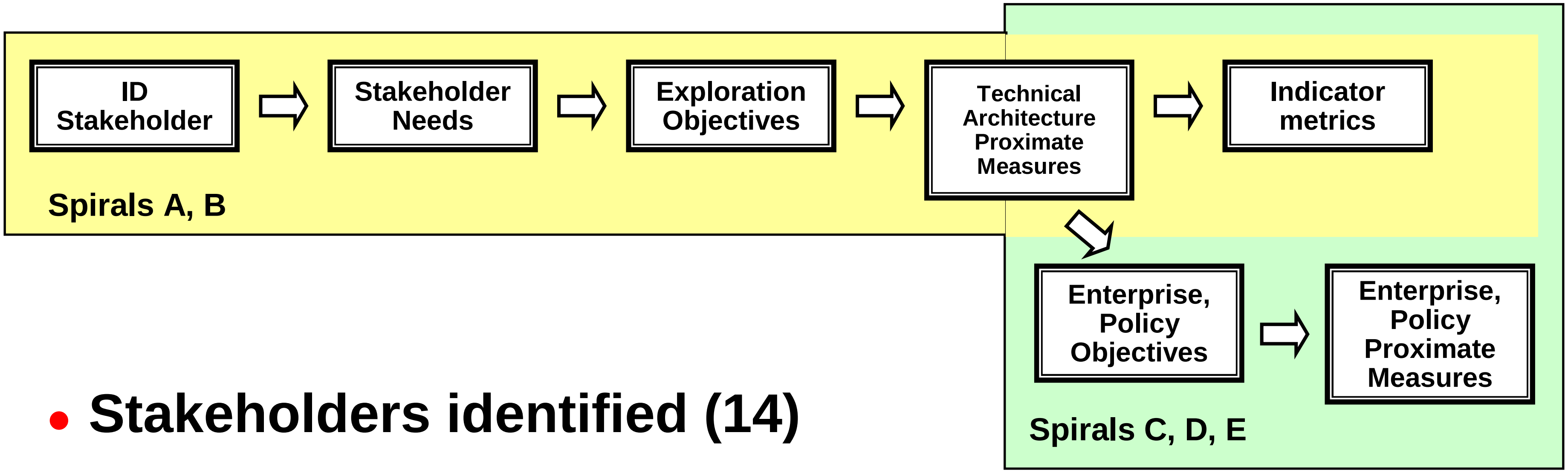
CEV

Value Enables Sustainability

- A sustainable exploration system must produce outputs that are valued by stakeholders
- Approach: analyze and develop metrics to quantify the flow of benefits from exploration activities to stakeholders
- Analysis of value objectives helps assess approaches for delivering value to the stakeholders:
  - Through the technical architecture
  - Delivered by the enterprise architecture
  - Robust to policy fluctuations

Deliberate focus on stakeholder value enables the proper design of technical system, organization, and policy to increase value delivered by the system over its decades-long lifecycle

Stakeholder Value Analysis Process



ID Stakeholder

Stakeholder Needs

Exploration Objectives

Technical Architecture Proximate Measures

Indicator metrics

Spirals A, B

Enterprise, Policy Objectives

Enterprise, Policy Proximate Measures

Spirals C, D, E

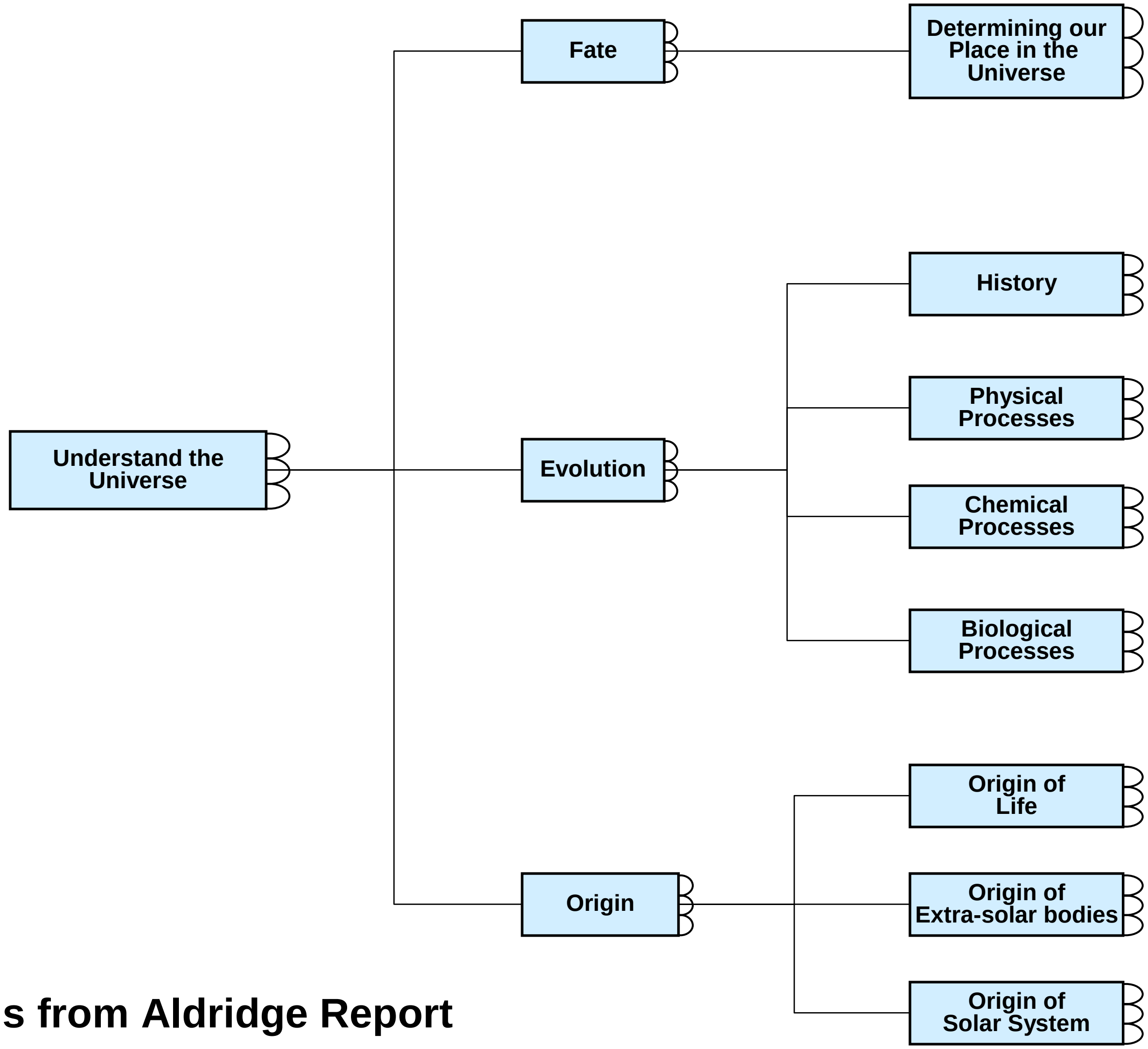
- Stakeholders identified (14)
- Stakeholder needs defined (~90)
- Exploration objectives (24)
- Technical architecture proximate measures (~18)
- Indicator metrics (~40)

Exploration System Stakeholders

- Addresses direct and indirect beneficiaries of space exploration activities
- Categorized into stakeholder super groups that correspond with general areas of societal impact

Stakeholders Addressed				
Exploration	**Science**	**Economic**	**Security**	**Public**
Explorers, Engineers, NASA	Scientists, NASA, Other US agencies	Commercial enterprises, Other US agencies, engineers	DoD and Intelligence, International Partners	Media, Educators, Executive Branch, Congress, NASA

Scientific Needs Diagram



Understand the Universe

Fate

Evolution

Origin

Determining our Place in the Universe

History

Physical Processes

Chemical Processes

Biological Processes

Origin of Life

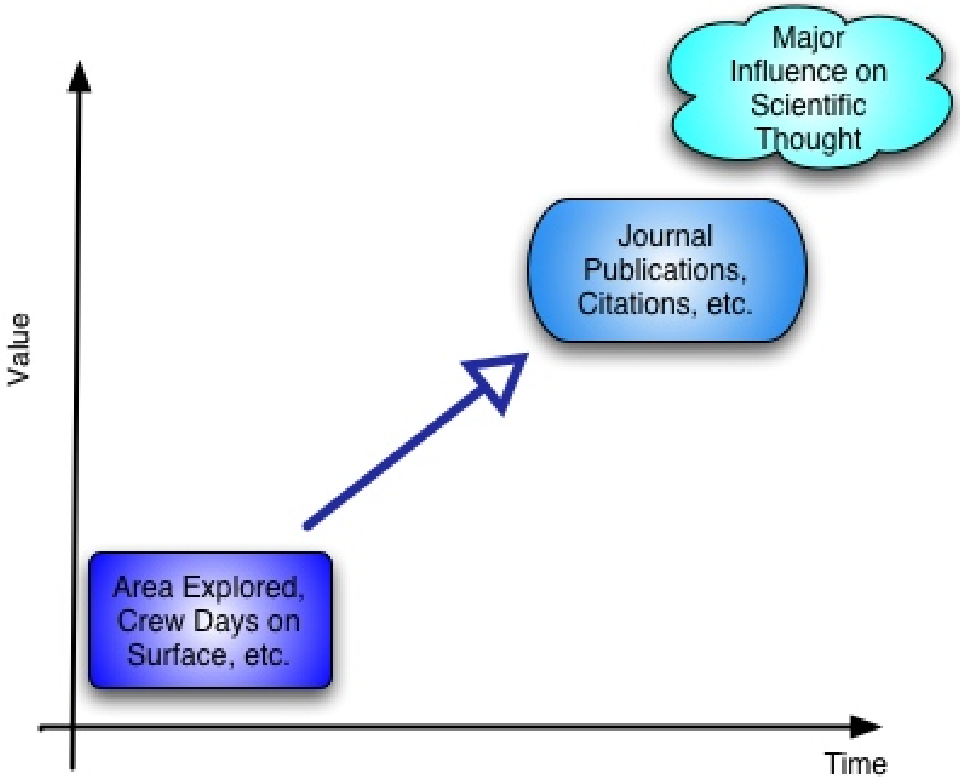
Origin of Extra-solar bodies

Origin of Solar System

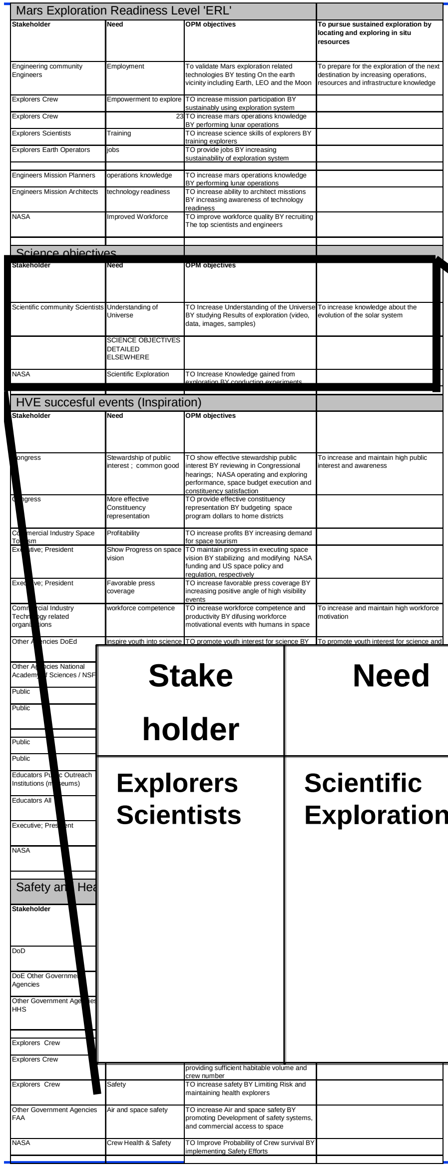
Definitions from Aldridge Report

Value, Metrics and Proximate Measures

- Value is subjective in the eyes of the beneficiary, is hard to measure, and is often only present once the mission is completed - e.g influence on scientific thought
- Value can be characterized by indicative metrics, but these too may require mission completion - e.g publications and citation
- In order to be useful for ranking of candidate architectures, metrics must be related to *proximate measures* that are trajectory measures toward value - e.g. area explored, etc.



Example: Explorer Value Flow to Architecture Metrics



Mars Exploration Readiness Level 'ERL'

Stakeholder	**Need**	**OPM objectives**	**To pursue sustained exploration by locating and exploring in situ resources**
Engineering community Engineers	Employment	To validate Mars exploration related technologies BY testing On the earth vicinity including Earth, LEO and the Moon	To prepare for the exploration of the next destination by increasing operations, resources and infrastructure knowledge
Explorers Crew	Empowerment to explore	TO increase mission participation BY sustainably using exploration system	
Explorers Crew	23	TO increase mars operations knowledge BY performing lunar operations	
Explorers Scientists	Training	TO increase science skills of explorers BY training explorers	
Explorers Earth Operators	jobs	TO provide jobs BY increasing sustainability of exploration system	
Engineers Mission Planners	operations knowledge	TO increase mars operations knowledge BY performing lunar operations	
Engineers Mission Architects	technology readiness	TO increase ability to architect misstions BY increasing awareness of technology readiness	
NASA	Improved Workforce	TO improve workforce quality BY recruiting The top scientists and engineers	

Science objectives

Stakeholder	**Need**	**OPM objectives**	
Scientific community Scientists	Understanding of Universe	TO Increase Understanding of the Universe BY studying Results of exploration (video, data, images, samples)	To increase knowledge about the evolution of the solar system
	SCIENCE OBJECTIVES DETAILED ELSEWHERE		
NASA	Scientific Exploration	TO Increase Knowledge gained from exploration BY conducting experiments	

HVE succesful events (Inspiration)

Stakeholder	**Need**	**OPM objectives**	
ongress	Stewardship of public interest ; common good	TO show effective stewardship public interest BY reviewing in Congressional hearings; NASA operating and exploring performance, space budget execution and constituency satisfaction	To increase and maintain high public interest and awareness
C ngress	More effective Constituency representation	TO provide effective constituency representation BY budgeting space program dollars to home districts	
Co mercial Industry Space To sm	Profitability	TO increase profits BY increasing demand for space tourism	
Exe utive; President	Show Progress on space vision	TO maintain progress in executing space vision BY stabilizing and modifying NASA funding and US space policy and regulation, respectively	
Exec ive; President	Favorable press coverage	TO increase favorable press coverage BY increasing positive angle of high visibility events	
Comm rcial Industry Techn ogy related organi tions	workforce competence	TO increase workforce competence and productivity BY difusing workforce motivational events with humans in space	To increase and maintain high workforce motivation
Other A encies DoEd	inspire youth into science	TO promote youth interest for science BY	To promote youth interest for science and
Other A cies National Academy f Sciences / NSF			
Public			
Public			
Public			
Public			
Educators Pu c Outreach Institutions (m eums)			
Educators All			
Executive; Pres ent			
NASA			

Safety an Hea

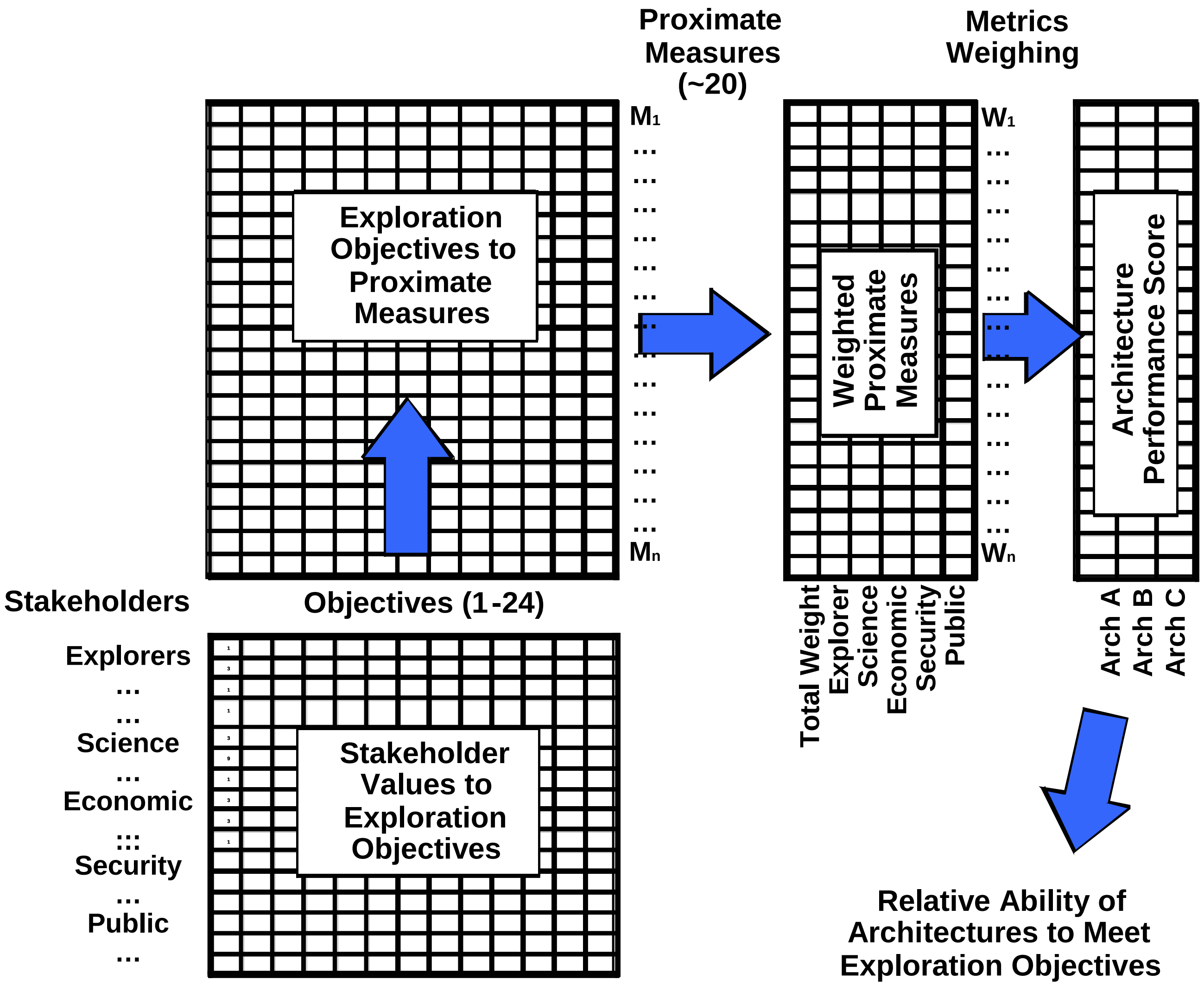
Stakeholder			
DoD			
DoE Other Governme Agencies			
Other Government Age ies HHS			
Explorers Crew			
Explorers Crew		providing sufficient habitable volume and crew number	
Explorers Crew	Safety	TO increase safety BY Limiting Risk and maintaining health explorers	
Other Government Agencies FAA	Air and space safety	TO increase Air and space safety BY promoting Development of safety systems, and commercial access to space	
NASA	Crew Health & Safety	TO Improve Probability of Crew survival BY implementing Safety Efforts	

- **Master record captures individual stakeholder needs, objectives, and flow to aggregated objectives and measures**
- **Architecture proximate measures and indicators metrics summarize common needs within and across stakeholder categories**

Stake holder	Need	Objective	Aggregated Objective	Proximate Measure	Indicator Metric
Explorers Scientists	**Scientific Exploration**	**TO Increase Knowledge gained from exploration BY conducting experiments**	**To increase knowledge about the solar system**	**Quality of Data**	**Recon and survey** **Spatial area of a given site that can be reached** **Diversity of sites** **Ability to temporally re-plan within mission (week to month)** **Ability to temporally re-plan and adapt in campaign**
				Amount of data	**Exploration payload delivered to M surface** **Observation days for crew on surface** **Observation days for robots on surface**

Ranking the Objectives for Trade Studies

- Traces value from stakeholders to relative performance of individual architectures
- Multiple ranking methods produce consistent high-level ranking of objectives
- Ranking highlights:
  - Enterprise architecture
  - Policy robustness
  - High BW comm
  - Knowledge



Proximate Measures (~20)

Metrics Weighing

M_1 … M_n

W_1 … W_n

Exploration Objectives to Proximate Measures

Weighted Proximate Measures

Architecture Performance Score

Stakeholders

Objectives (1-24)

Explorers
…
…
Science
…
Economic
:::
Security
…
Public
…

Stakeholder Values to Exploration Objectives

Total Weight
Explorer
Science
Economic
Security
Public

Arch A
Arch B
Arch C

Relative Ability of Architectures to Meet Exploration Objectives

Sustainability: Policy Robustness

- **Background study on the policy robustness of major multi-year DoD programs, and the factors that make programs robust to the 1, 2 and 4 year policy cycles**

- **Initial metrics and guidelines are:**
  - **Better to *satisfy all stakeholders a minimum amount* than to satisfy a few stakeholders a great deal**
  - ***Cost must be "flat"* across the program**
  - ***Steady cadence of successes*, i.e., High Visibility Events**

Sustainability: Risk

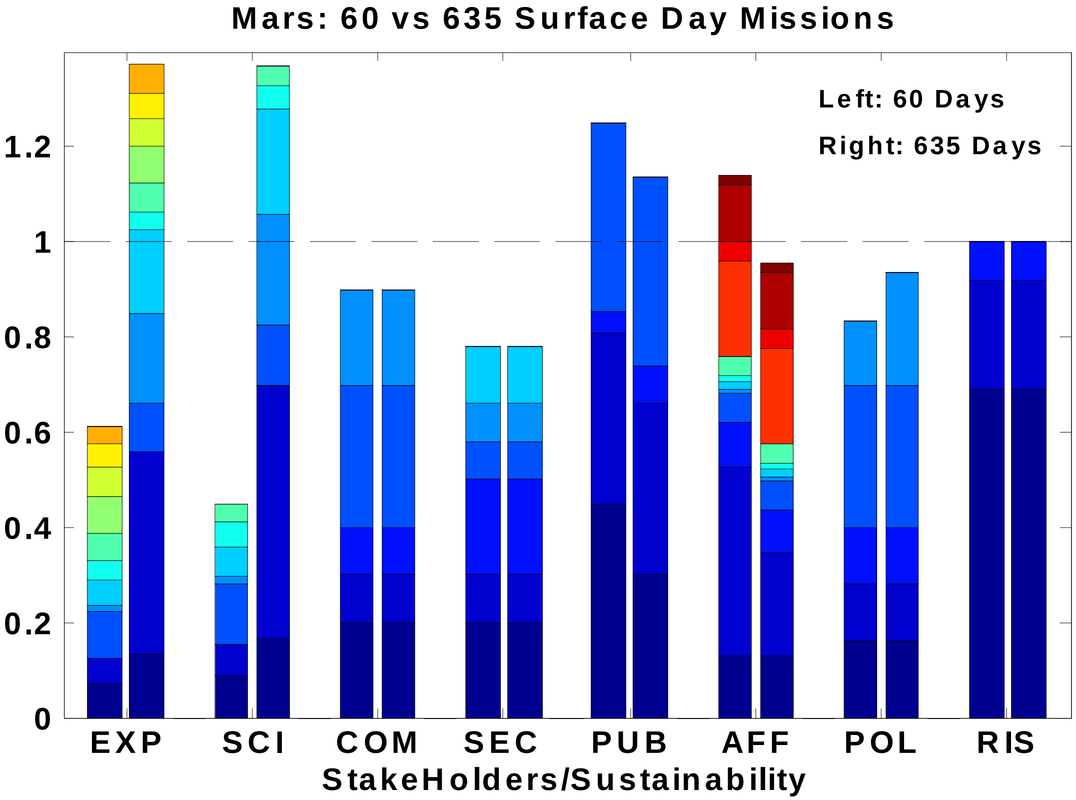
- **Our preliminary approach to risk is Hazard-based and includes the following steps:**
  - ***Identify high-level hazards*** **for each mission phase and start tracking process**
  - **Assign a *severity* index to each hazard based on the potential losses to Human, Mission, Equipment, and Environment**
  - **Evaluate the hazard *mitigation* effect of architectural options and identify additional mitigation strategies/options**
  - **Compute a *relative hazard level* based on the mitigation potential of the combined architectural decisions**
  - **As needed, combine the relative hazard levels into a single risk/safety metric for each category (Human, Mission,…)**
- **Particularly well suited to unprecedented and integrated hardware/software systems**

Sustainability: Affordability

- Developed a set of proximate metrics and indicators for affordability that allow relative ranking between architectures
- Development and operational cost
  - Hardware and transportation systems: dry mass of unique elements, wet mass, number of unique major individual elements in program
  - Communications and navigation system: precision, response time, gaps, availability, data volume, mass of elements
  - Software/Autonomy: precedentedness, criticality/reliability, complexity, timing requirements and constraints, level of ground support required
- Use of moon as development for Mars (commonality)
  - Development demonstrated on moon
- Programmatic risk
  - Decoupling of major program elements
  - New technology developed
  - Political risk of technology development (e.g. nuclear)

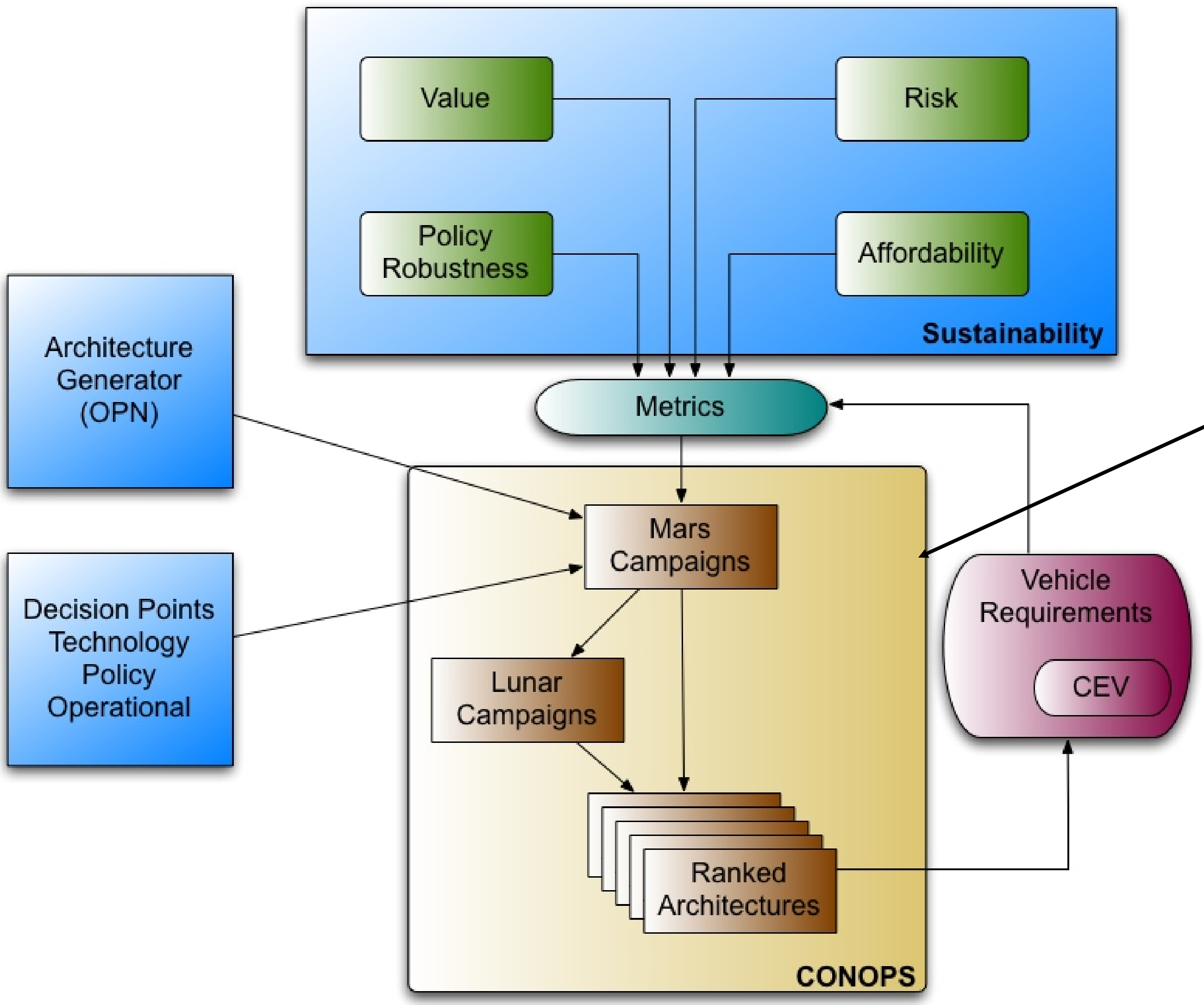
Metrics Describe Overall Exploration Sustainability

- Metrics Categories
  - Explorers
  - Science
  - Commercial
  - Security
  - Public
  - Affordability
  - Policy Robustness
  - Risk



- Outcome
  - Metrics help define relative exploration system sustainability during trade studies
  - Trades among categories are subjective and ultimately up to the "decision maker"

From Requirements to Surface Operations



The knowledge that drives Value to the exploration, science and public stakeholders is largely derived from the surface ops

Mars-Back ™

- Ultimate goal is sustainable human and robotic exploration of Mars
- Approach:
  - Define candidate Mars missions that produce high value
  - Derive lunar missions to increase Mars Exploration Readiness Level
    - Secondary objective maximizes lunar science and exploration goals
  - Develop architectures in support of Mars and moon missions
  - Refine architectures to deliver maximum value

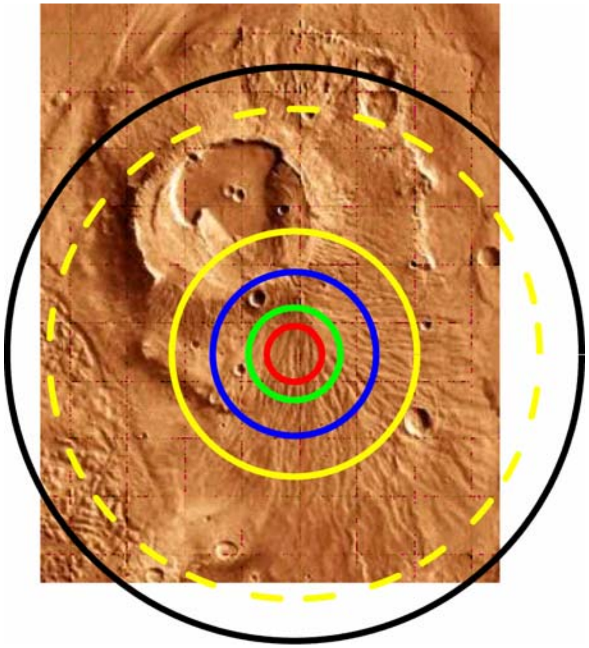
Mars Surface Operational Architecture

- During Spiral B, two candidate Mars missions were studied:
    - Short stay (~60 Surface Day Mission, ~535 day total)
    - Long stay (~600 Surface Day Mission, ~930 day total)
- Main exploration activities will be:
    - Sample collection, searching for water and life by surface sample collection and meter depth drilling
    - Interacting with the robots that will have been exploring the area before the arrival of humans
- Examine architecture for:
    - Surface mobility
    - Habitation
    - Power
    - Deferred: ISRU, exploration measurement, consumables, robotic exploration

Surface Mobility - Mars

- Martian topography is made up of diverse terrain including: polar caps, massive volcanoes, ice rich plains, gullies, channels, and mesas, at large length scales
- Examine 6 mobility architectures, each with tolerance for total failure of primary system
  - The pressurized rovers are sized for a traverse duration of 3 Earth days
- Pressurized rovers give range needed for exploration of diverse features, and loiter time far from base

11km	🟥	Walk (2.7 km/h)
18 km	🟩	1 open rover (12 km/h)
32 km	🟦	2 open rovers (12km/h)
48km	🟨	1 press. rover + 1 open at base
96 km	🟨 🟨 🟨	1 press. rover + 1 open in tow
112 km	⬛	2 pressurized rovers (15 km/h)



Mars - Apollinaris Patera

Surface Mobility - Mars Back to Moon

- The moon may be considered to consist of four major units: mare, highlands, craters, and shadowed regions that may contain ice
- An area of primary lunar science interest is the poles
- MERL considerations:
  - Crater slopes on moon and Mars have comparable inclinations
  - Open rovers will give range to several craters of eternal darkness
  - Pressurized rovers can be added later to explore nearby basins
- Pressurized rover will needed for Mars, and can be tested on moon
- Open rovers will be useful at both moon and Mars

11km	🟥	Walk (2.7 km/h)
18 km	🟩	1 open rover (12 km/h)
32 km	🟦	2 open rovers (12km/h)
48km	🟨	1 press. rover + 1 open at base
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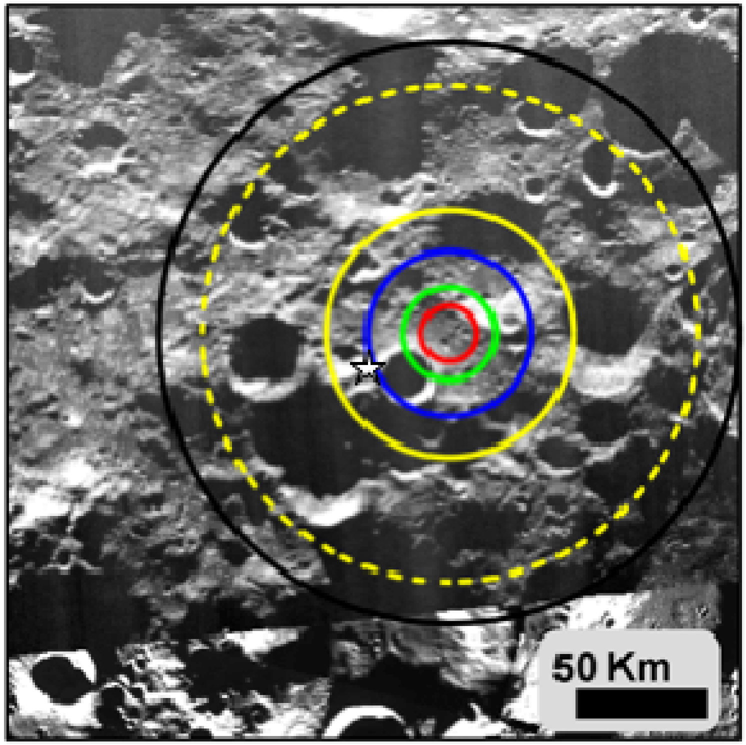
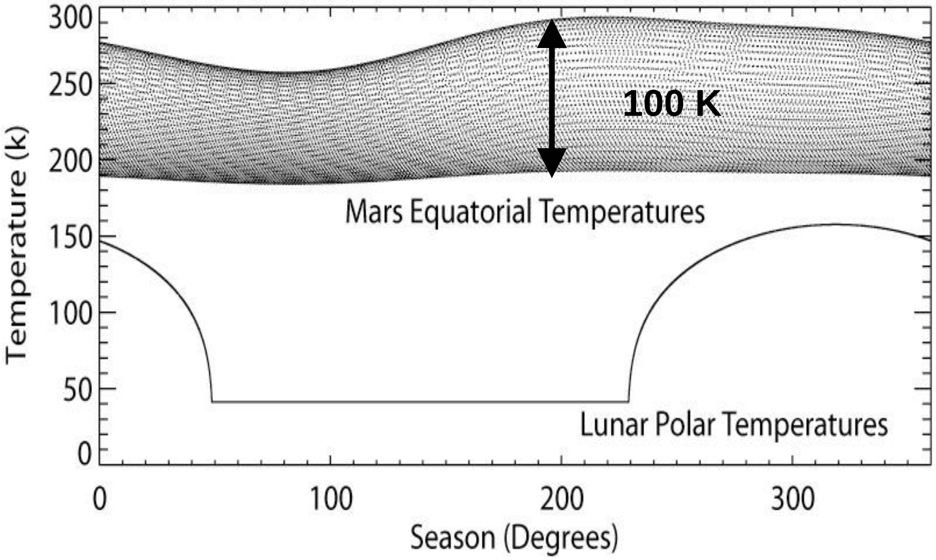
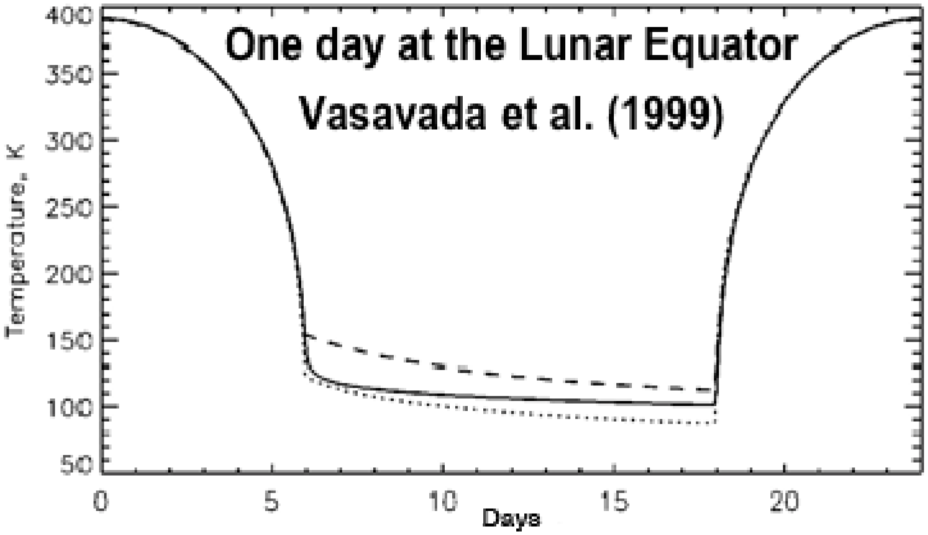


Lunar South pole ☆

Habitation - Mars/Moon Thermal

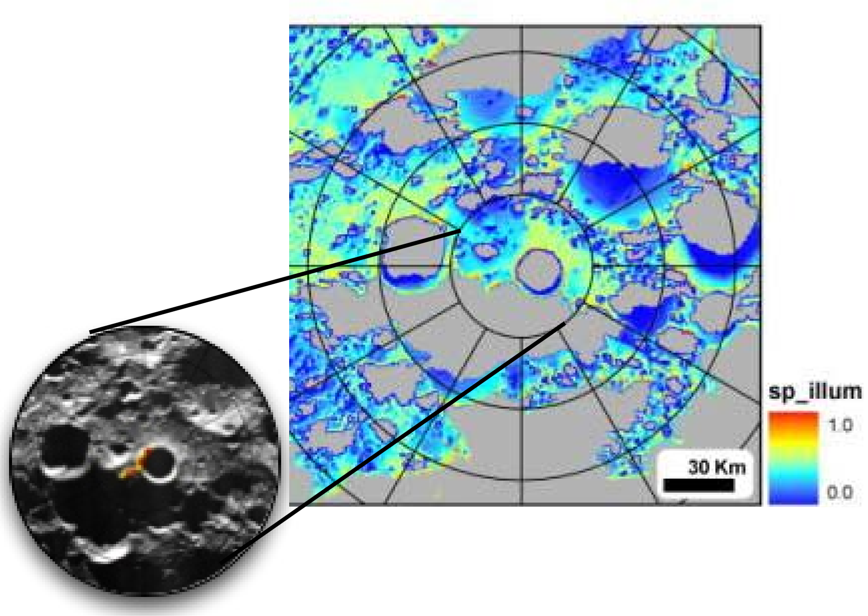
- Mars reference architecture is habitat near Martian equator, for up to 600 days: large diurnal temperature range (100K), but small seasonal temperature changes
- MERL considerations - two Lunar environments considered:
  - Lunar pole (within the 1.5^o of axis tilt): no diurnal temperature changes, but large seasonal changes
  - Lunar equator: huge diurnal temperature range (300 K), but virtually no seasonal change
- During summer of up to 150 Earth days, lunar poles have temp within about 50 K, and range is about 100 K below that of Mars
- Run up to 150 day missions at lunar poles, and design for slightly harsher thermal conditions





Power - Mars/Moon Insolation

- Mars reference architecture is solar power near equator, reduced flux, Martian day cycle from day to night
- MERL considerations - two Lunar environments considered
  - Lunar equator: 14 earth day lunar night probably precludes solar as primary option
  - Lunar pole: high topography is permanently illuminated
    - >630 m at pole, but must also consider local topography.
    - >1700 m at 89°
  - South pole has about 28 km^2 which pass this test (shown above in red)
  - North polar topography is everywhere too low to be illuminated in winter
- Use solar power plant in regions of eternal sunlight for lunar base



Surface Operations Objectives - Moon

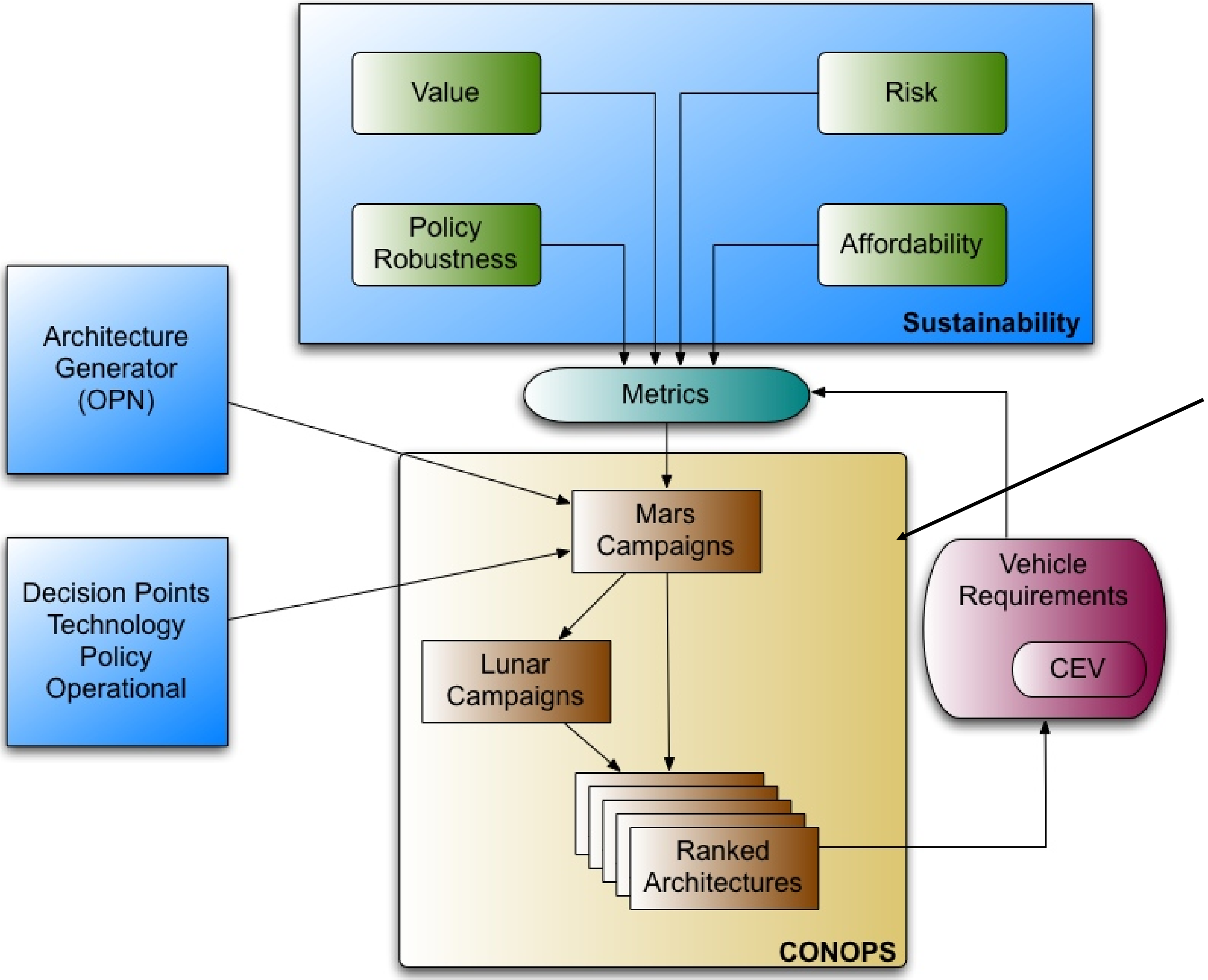
- Primary objective of increasing Mars Exploration Readiness Level achieved by Lunar testing of Martian exploration techniques, procedures and equipment
- Poles operationally advantageous for long stays
  - Areas 1.5 degrees from the poles are permanently illuminated during the 6-month lunar summers
  - Sun angle is low; surface temperatures are moderated
  - Topographically high areas are permanently lit at South Pole
- Secondary objective of maximizing lunar exploration/science benefit achieved
  - “Craters of eternal darkness” permit the investigation of “excess” hydrogen
  - Geology and Aitken basin near South Pole provide numerous scientifically interesting exploration destinations

Lunar Campaign - Accrete Assets

The objective of the lunar campaign is to increase the MERL
Land on Equator for first mission, but quickly move on to polar region in order to start accretion of assets for long term stays

Mission Description	Capability Acquired	Asset Accretion	Risk Retired
Equatorial landing No Hab, No Rovers	Manned landing	Navigation, science, communication equipment	Precision manned landing
Polar landing No Hab, 1 Open Rover	Operations on poles	1 Open Rover, other equipment	Polar survivability/operations
Polar landing Hab, 1 Open Rover	Medium term stay, larger traversable area	1 Additional Rover, Hab	Surviving lunar day/night
Polar landing Pressurized rover, more crew (?)	Over-night excursions, larger crew support on base	Pressurized rover, additional infrastructure	Over-night stays away from base
Polar landing Power plant	Long term stay, power generation	Power plant	Power generation on surface, long duration stay on surface
Polar landing ISRU equipment	In-Situ resource utilization	Heavy machinery, ISRU plant	Surface resources utilization, operation of heavy equipment

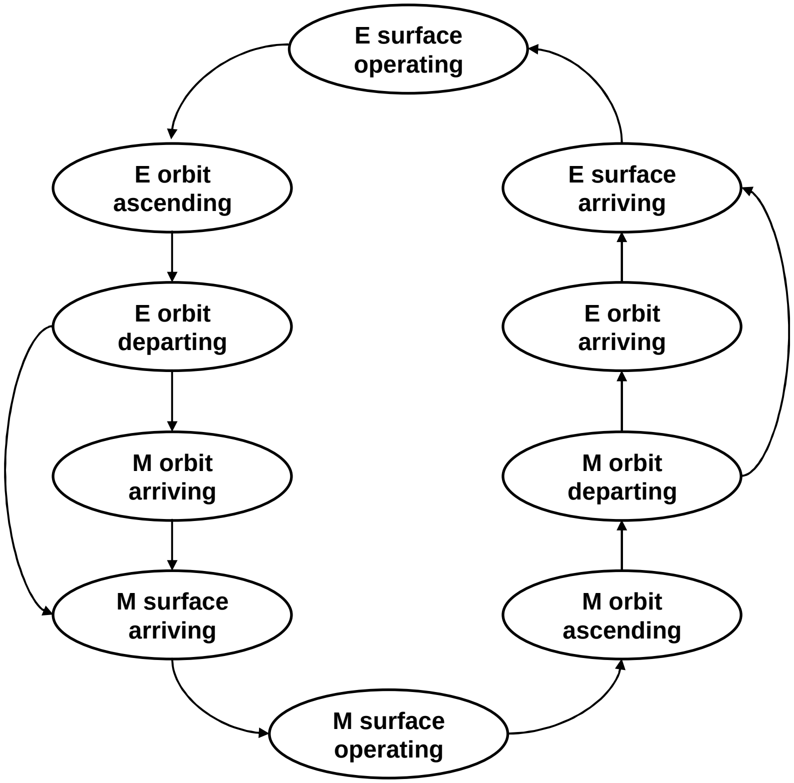
From Requirements to Transportation



The surface ops are supported by transportation, which also delivers value to the security and commercial stakeholders

Transportation Architecture Generator

- Systematically and comprehensively explore the space of transportation itineraries from LEO to M surface
- Created a discrete event simulator (OPN) which includes all possible operational sequences and associated hardware elements
- Simplified version produces over 600 itineraries for one M mission



Transportation Architecture Generator

See associated “.mov” file

QuickTime™ and a
Animation decompressor
are needed to see this picture.

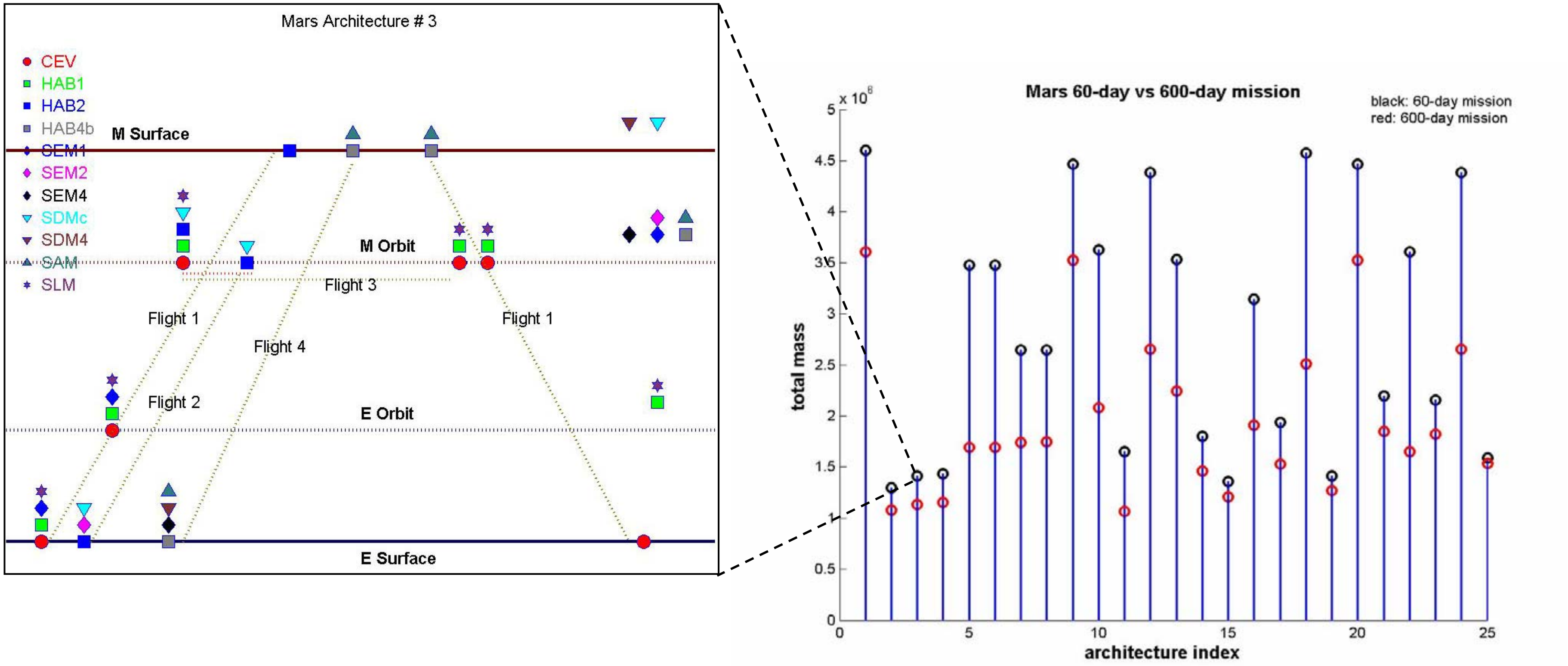
Technology/Policy/Operational Branches

- Technology
  - ISRU
  - Aerocapture
  - Nuclear Thermal Rockets
  - Solar/Nuclear Electric Propulsion
  - Nuclear surface power
  - Level of autonomy
  - Highly Elliptical Orbital Rendezvous
  - Rendezvous in transit
  - Artificial gravity
  - High-closure ECLSS (H_20, O_2)
  - Low boil-off propellant storage
  - In-space propellant transfer
- Policy/operational
  - HLLV (yes/no, size)
  - Level of abort options
  - Nuclear (yes/no)
  - Free-return trajectory (yes/no)
  - Initial Mars mission duration (short/long)
  - De-investing in the moon
  - Level of international involvement
  - Level of commercial involvement

For each itinerary, there are technical level trades, and technology/policy/operational decision branches that are set

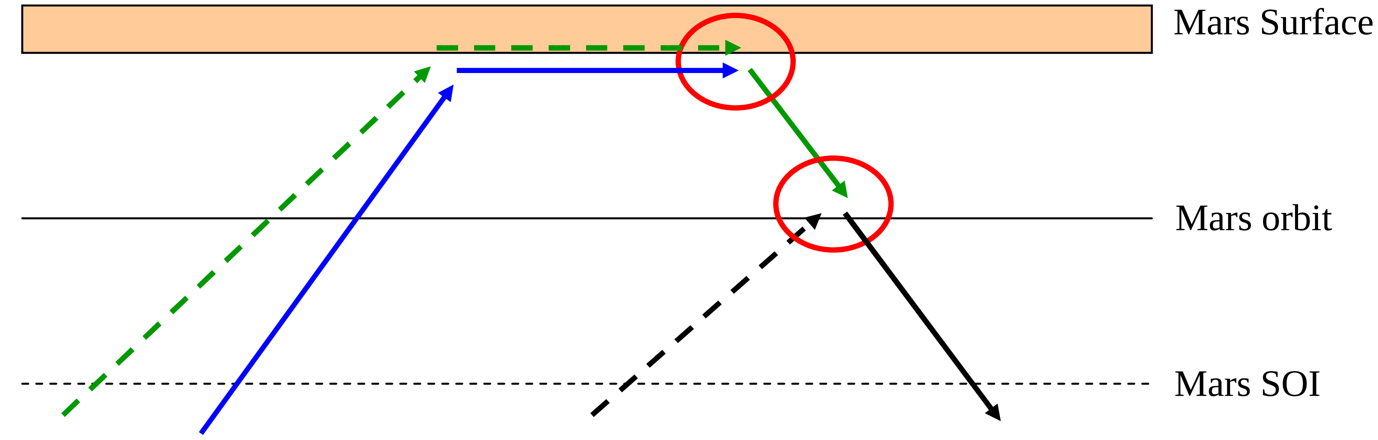
Architecture Screening

- **For over 600 itineraries, and fixed technology/operational decisions, optimization determines best mix of sub-system technologies**
- **Automated evaluation and visualization tools developed to screen and analyze results, ranked by IMLEO as primary metric for cost**

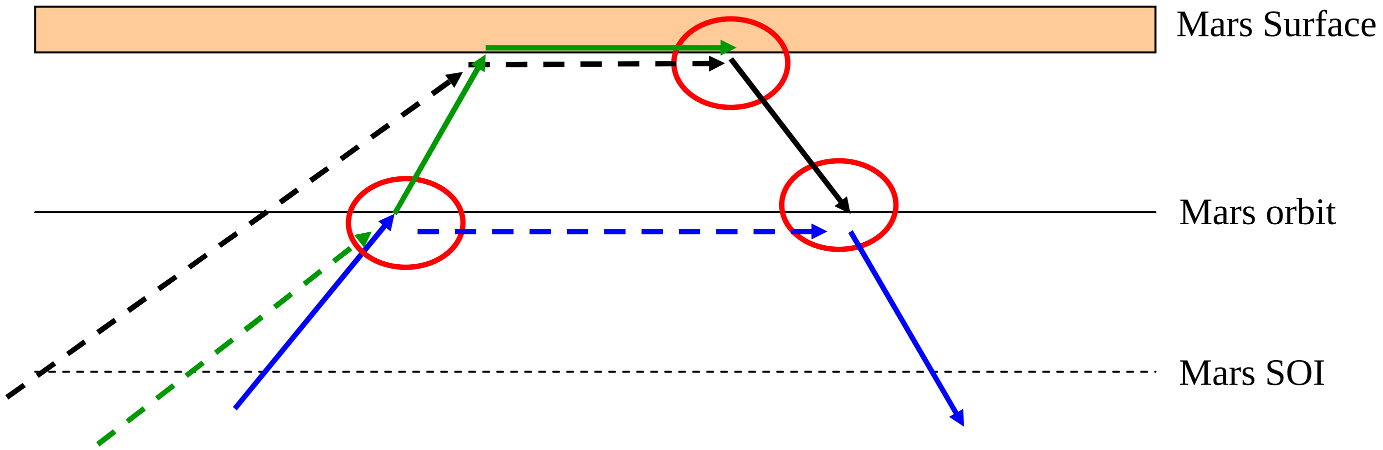


Mars Trade Baseline Examples

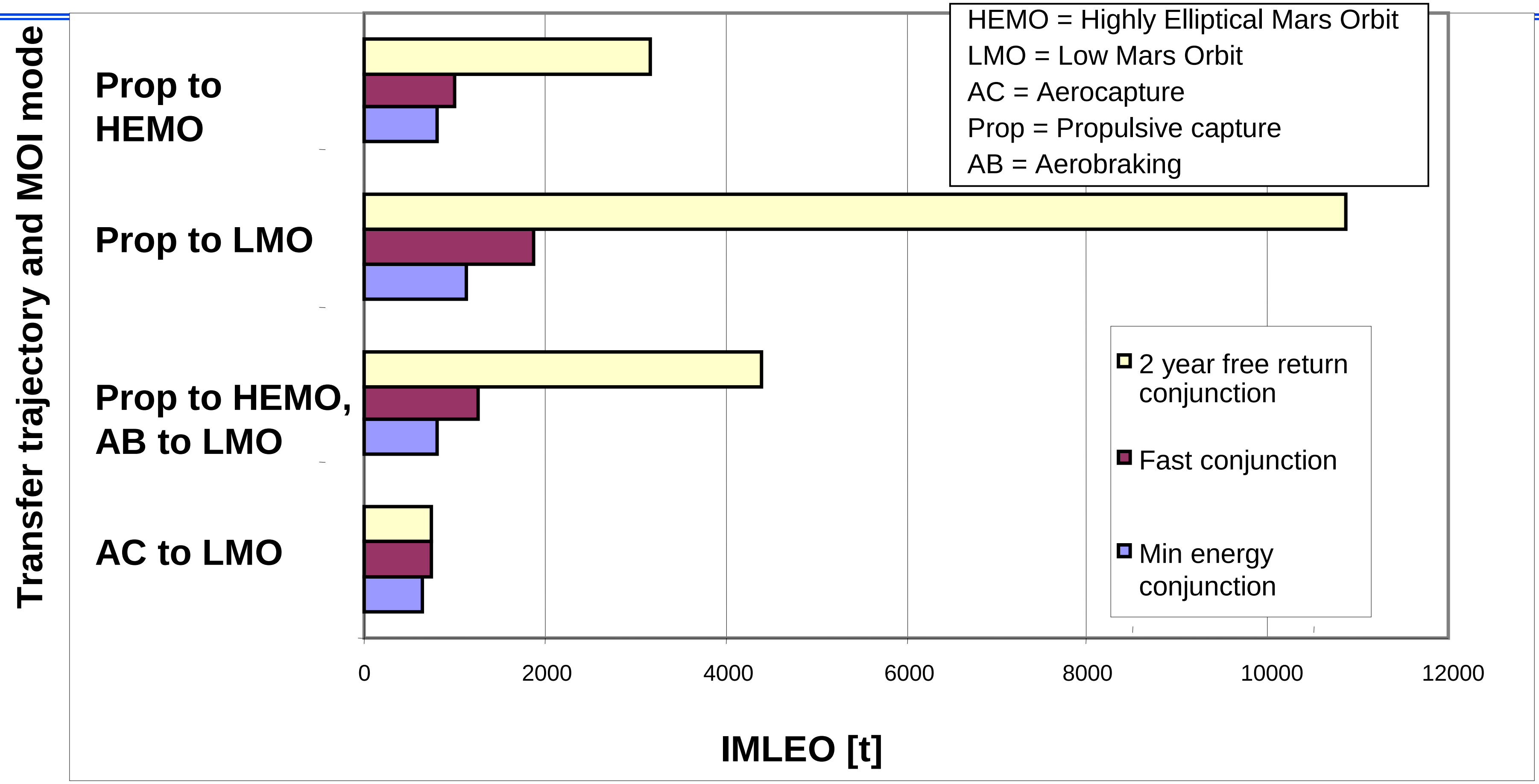
Arch 2: NASA JSC Mars Design Reference Mission



Arch 3: DRM/Apollo Blend



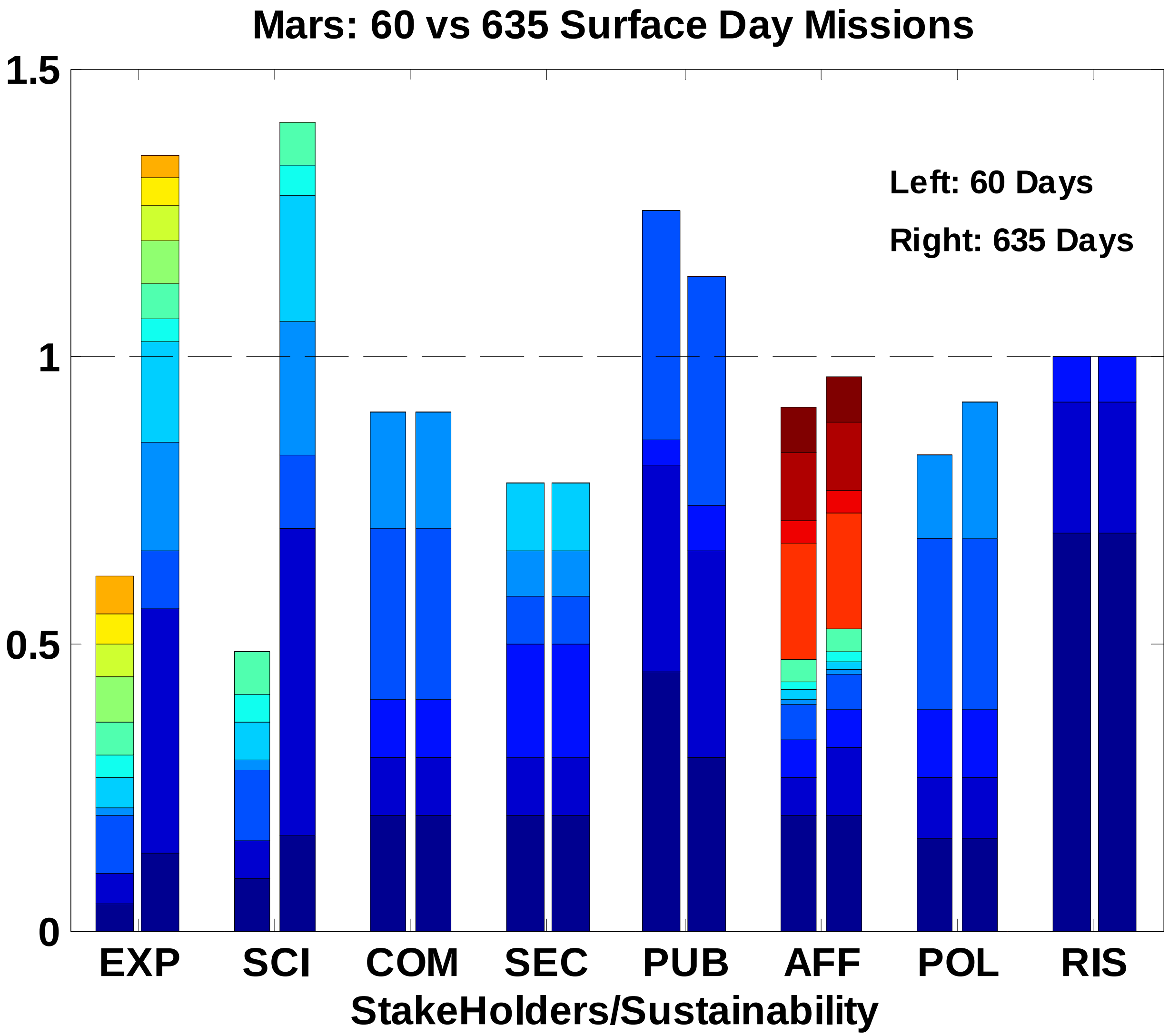
Technology/Transit/Insertion Operational Options



To keep IMLEO below 1000t requires:

Aerocapture, which supports both abort to orbit and free return, or Rendezvous in a Highly Elliptical Mars Orbit (HEMO), which supports abort to orbit, but not free return

Short vs. Long Mars Mission Metrics



- Mars 60 Day
  - Higher value for Public Stakeholder due to occurrence of high visibility event
  - Lower Policy Robustness metric due to low benefit to Scientific stakeholder
- Mars 635 Day
  - Longer surface stay results in significantly higher benefits to Explorer and Scientific stakeholders
  - Higher Affordability metric due to significantly less mass in LEO

Commonality and Modularity of Propulsion Systems

2 Approaches:

1. Design for Mars, reuse hardware for lunar missions

- Pros:
  - Mars requirements are accommodated exactly
  - Design of hardware elements spread out over longer time
- Cons:
  - Necessitates design of more hardware elements

2. Design for moon and Mars, modularize propellant tanks, structure and engines on the subsystem level

- Pros:
  - Necessitates less hardware design
  - Economies of scale
- Cons:
  - Higher development risk (complex modular propulsion stage)

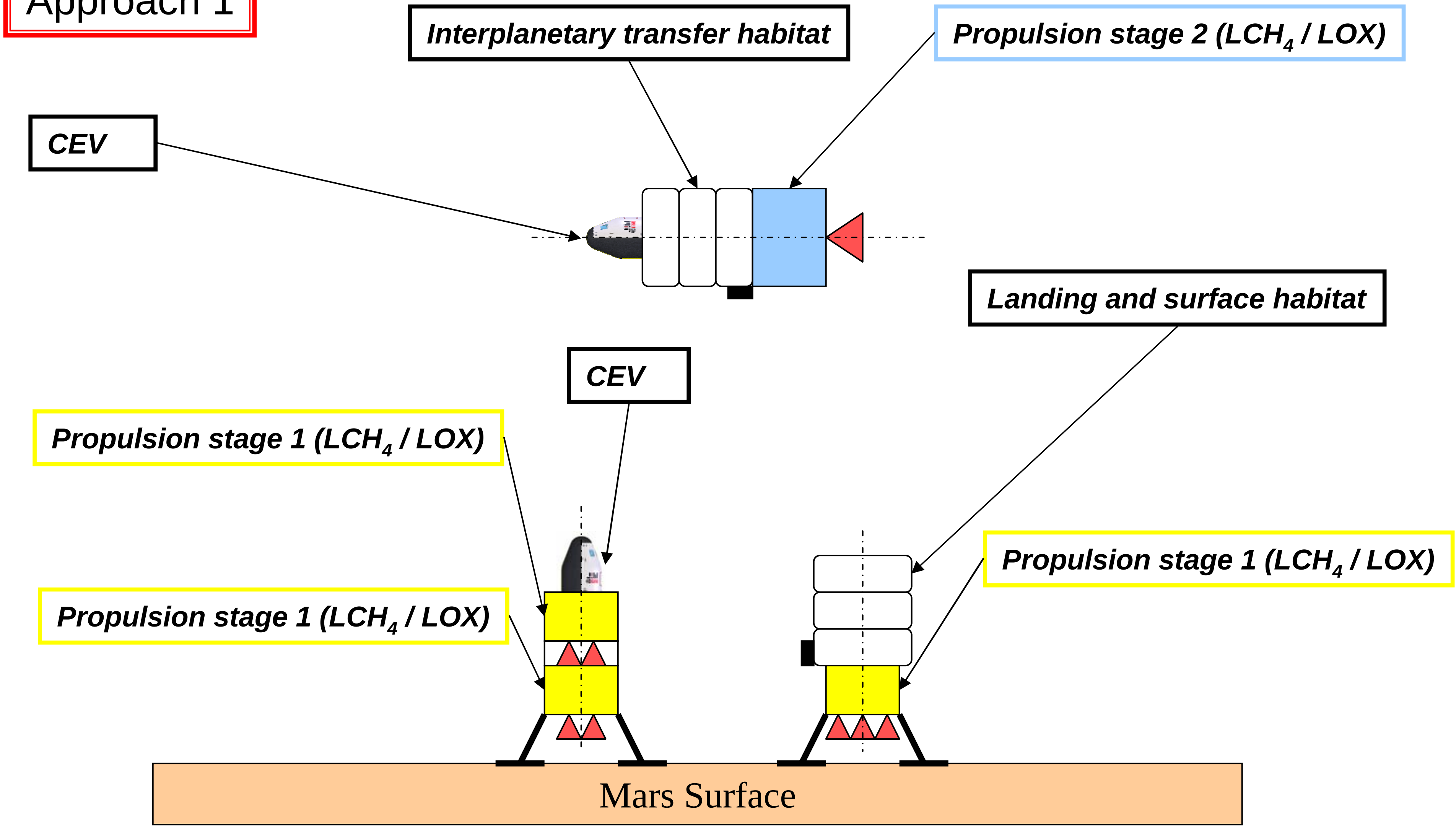
6 %

Mass overhead due to commonality / modularization (preliminary)

10 %

Long Mars Mission Hardware (Architecture 3)

Approach 1



Interplanetary transfer habitat

Propulsion stage 2 (LCH$_4$ / LOX)

CEV

Landing and surface habitat

CEV

Propulsion stage 1 (LCH$_4$ / LOX)

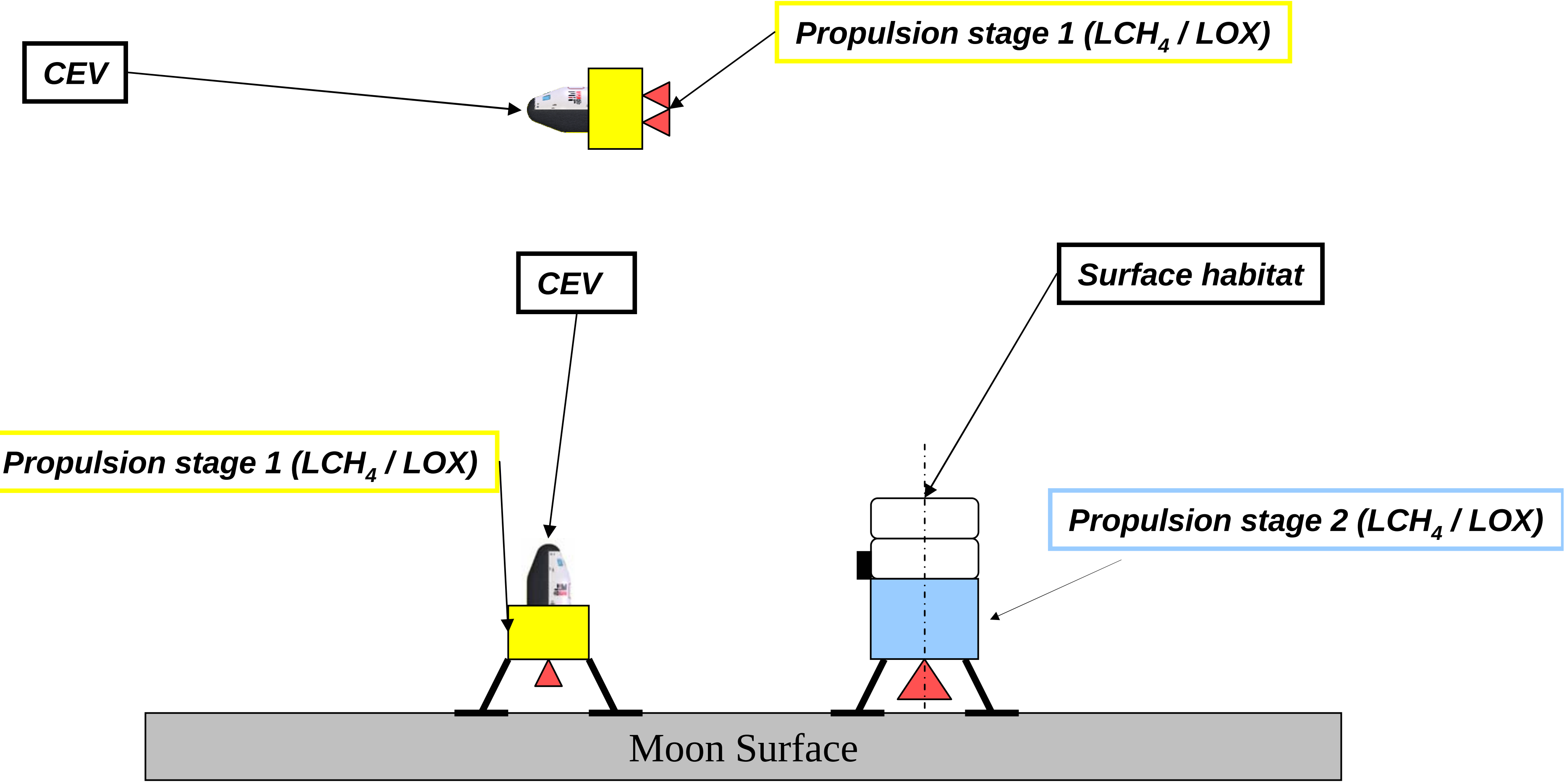
Propulsion stage 1 (LCH$_4$ / LOX)

Propulsion stage 1 (LCH$_4$ / LOX)

Mars Surface

Lunar variant (180 day surface stay)

Approach 1



CEV

Propulsion stage 1 (LCH_4 / LOX)

CEV

Surface habitat

Propulsion stage 1 (LCH_4 / LOX)

Propulsion stage 2 (LCH_4 / LOX)

Notional Hardware Development Roadmap

Approach 1

LEO Mission Hardware (Spiral 1)

CEV (22 m^3)

Short Moon Mission Hardware (Spiral 2)

Propulsion stage 1 (LCH_4 / LOX):
Structural mass: 1402 kg
Maximum propellant mass: 12408 kg

Engine 1 (LCH_4 / LOX):
Engine mass: 263 kg
Engine thrust: 76 kN

Propulsion stage (LH_2 / LOX):
TMI / TLI

Engine (LH_2 / LOX):
TMI / TLI

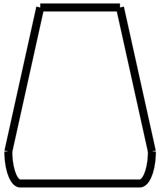
Long Moon Mission Hardware (Spiral 3)

Propulsion stage 2 (LCH_4 / LOX):
Structural mass: 8418 kg
Maximum propellant mass: 74495 kg

Engine 2 (LCH_4 / LOX):
Engine mass: 1042 kg
Engine thrust: 447.7 kN

Habitat “Plugs” and “End-caps”:
Pressurized volume: 114 m^3 / plug
Wet mass up to 21,000 kg

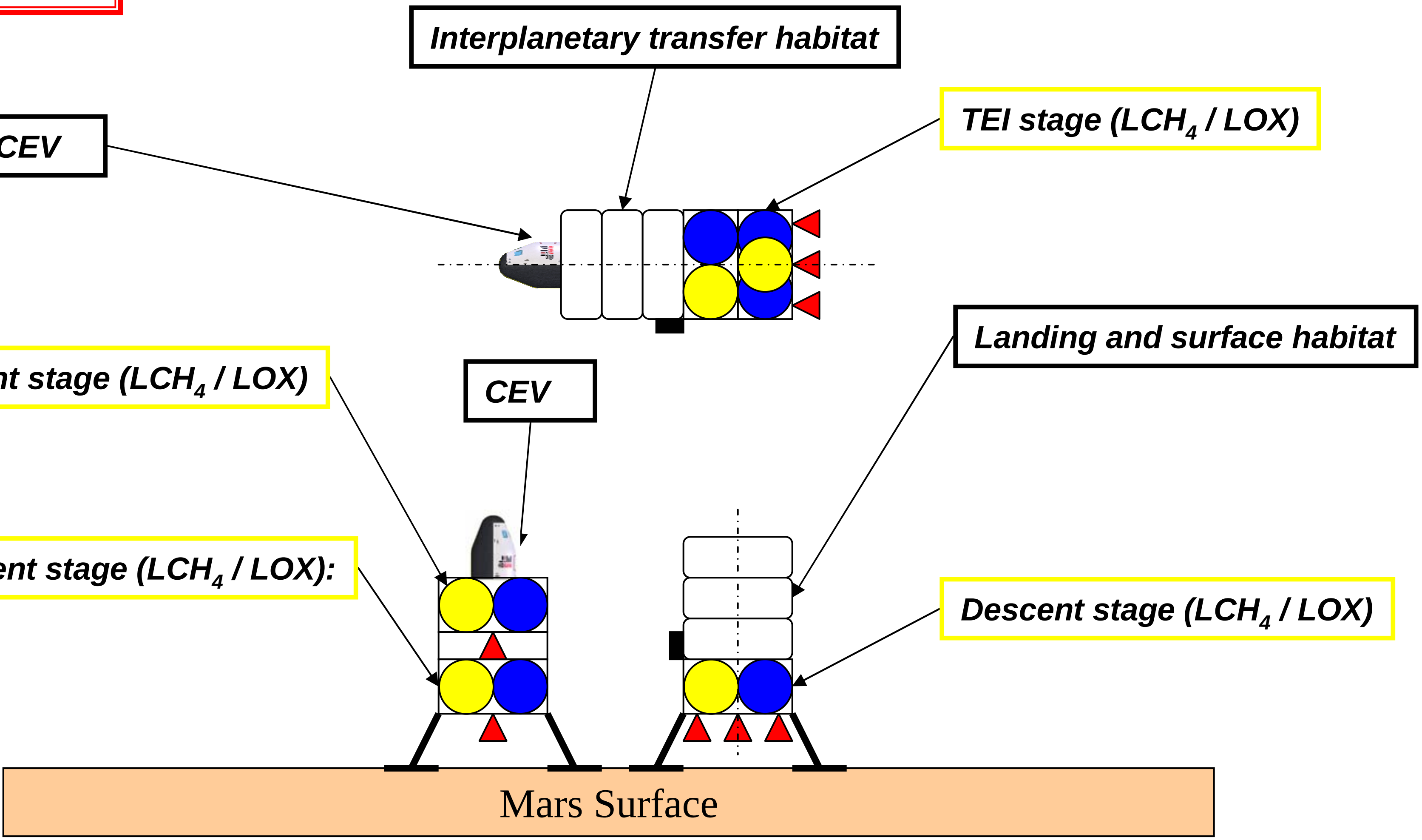
Mars Mission Hardware (Spiral 4+)



Heat protection for Mars Aerocapture and Aeroentry

Long Mars Mission (Architecture 3)

Approach 2



Interplanetary transfer habitat

CEV

TEI stage (LCH_4 / LOX)

Landing and surface habitat

Ascent stage (LCH_4 / LOX)

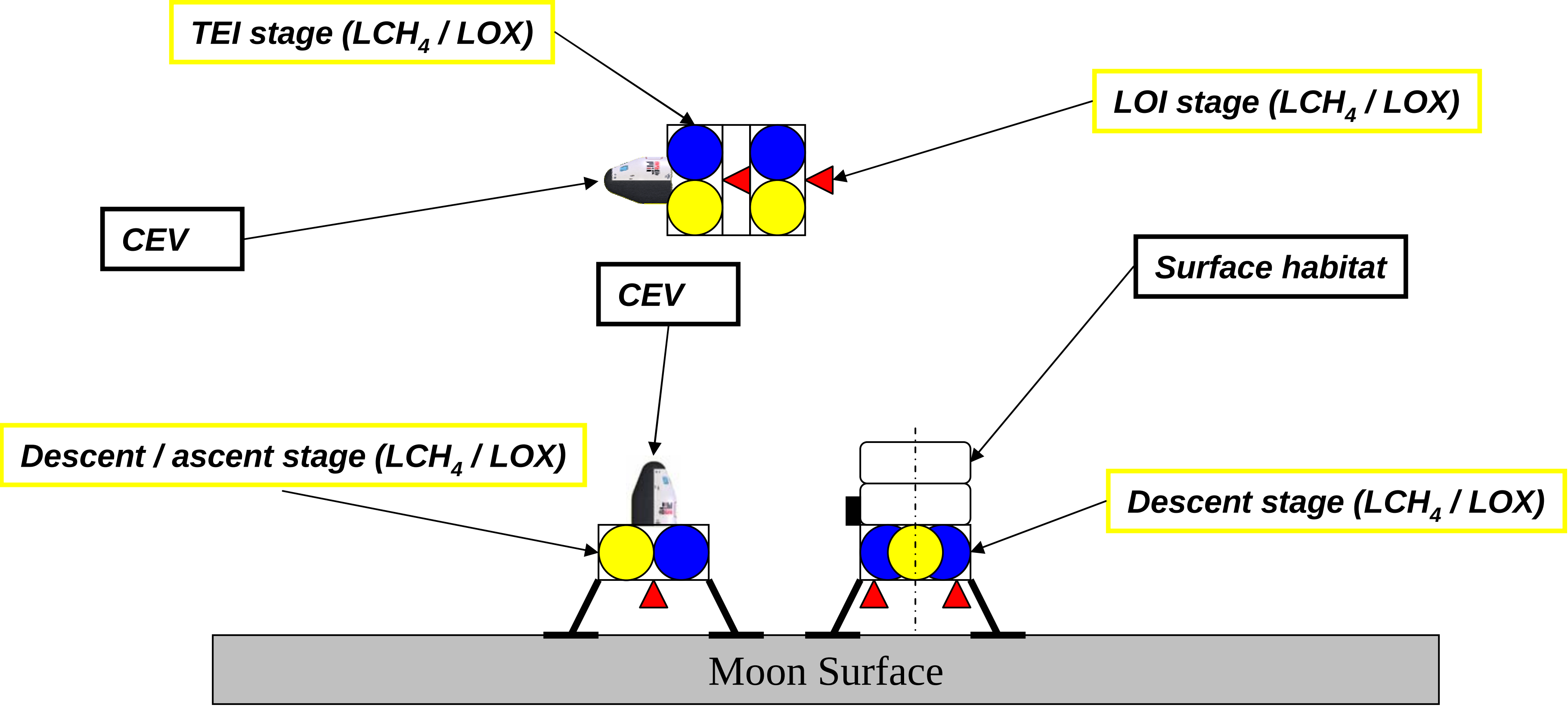
CEV

Descent stage (LCH_4 / LOX):

Descent stage (LCH_4 / LOX)

Lunar Variant (180 Day Surface Stay)

Approach 2



TEI stage (LCH_4 / LOX)

LOI stage (LCH_4 / LOX)

CEV

CEV

Surface habitat

Descent / ascent stage (LCH_4 / LOX)

Descent stage (LCH_4 / LOX)

Notional Hardware Development Roadmap

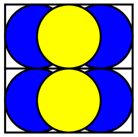
Approach 2

LEO Mission Hardware (Spiral 1)

CEV (22 m^3)

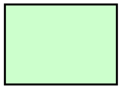
Short Moon Mission Hardware (Spiral 2)

Propulsion stage (LCH$_4$ / LOX):
Maximum structural mass: 12457 kg
Maximum propellant mass: 110240 kg

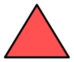


Engine 1 (LCH$_4$ / LOX):
Engine thrust: 185 kN

Propulsion stage (LH$_2$ / LOX):
TMI / TLI



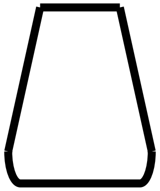
Engine (LH$_2$ / LOX):
TMI / TLI



Long Moon Mission Hardware (Spiral 3)

Habitat "Plugs" and "End-caps":
Pressurized volume: 114 m^3 / plug
Wet mass up to 21,000 kg

Mars Mission Hardware (Spiral 4+)



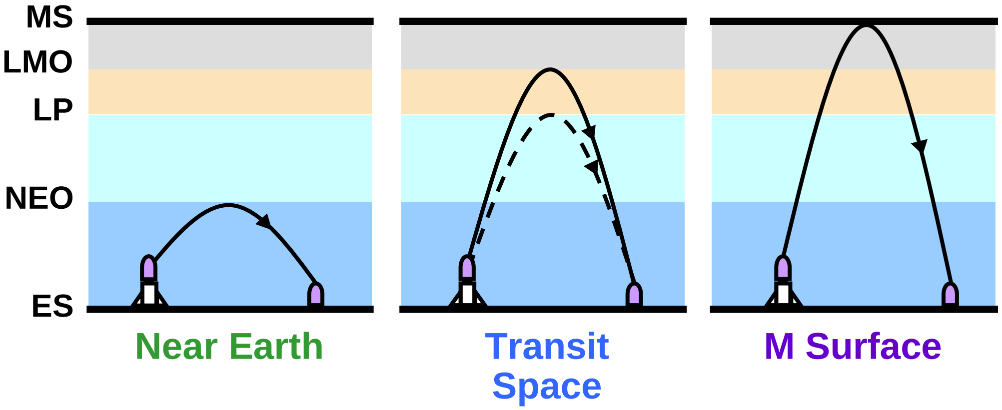
Heat protection for Mars Aerocapture and Aeroentry

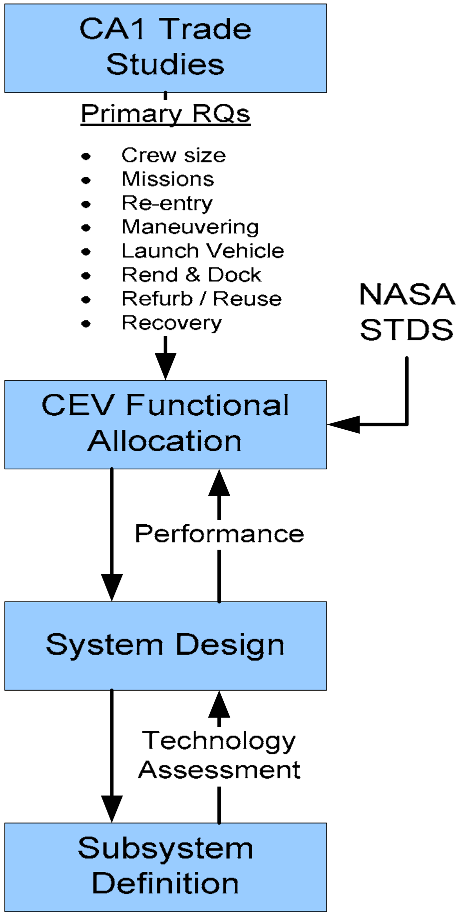
Requirements Flow-Down to CEV

- **Primary CEV allocation from CA1 architectures, currently carrying RQs for multiple destinations**

Near Earth	Remains in Earth vicinity
Transit Space	Orbits in destination vicinity
M Surface	Achieves destination surface

- **CEV design trade studies lead to subsystem definition**
  - Performance and technology assessment feedback to CEV RQs
- **Established DOORS database with CEV RQs and links to trade studies**




CA1 Trade Studies

Primary RQs

- Crew size
- Missions
- Re-entry
- Maneuvering
- Launch Vehicle
- Rend & Dock
- Refurb / Reuse
- Recovery

NASA STDS

CEV Functional Allocation

Performance

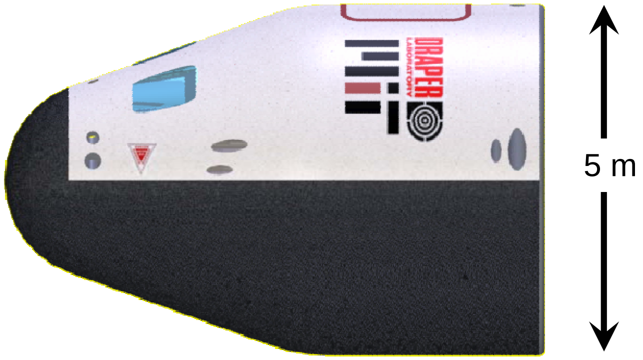
System Design

Technology Assessment

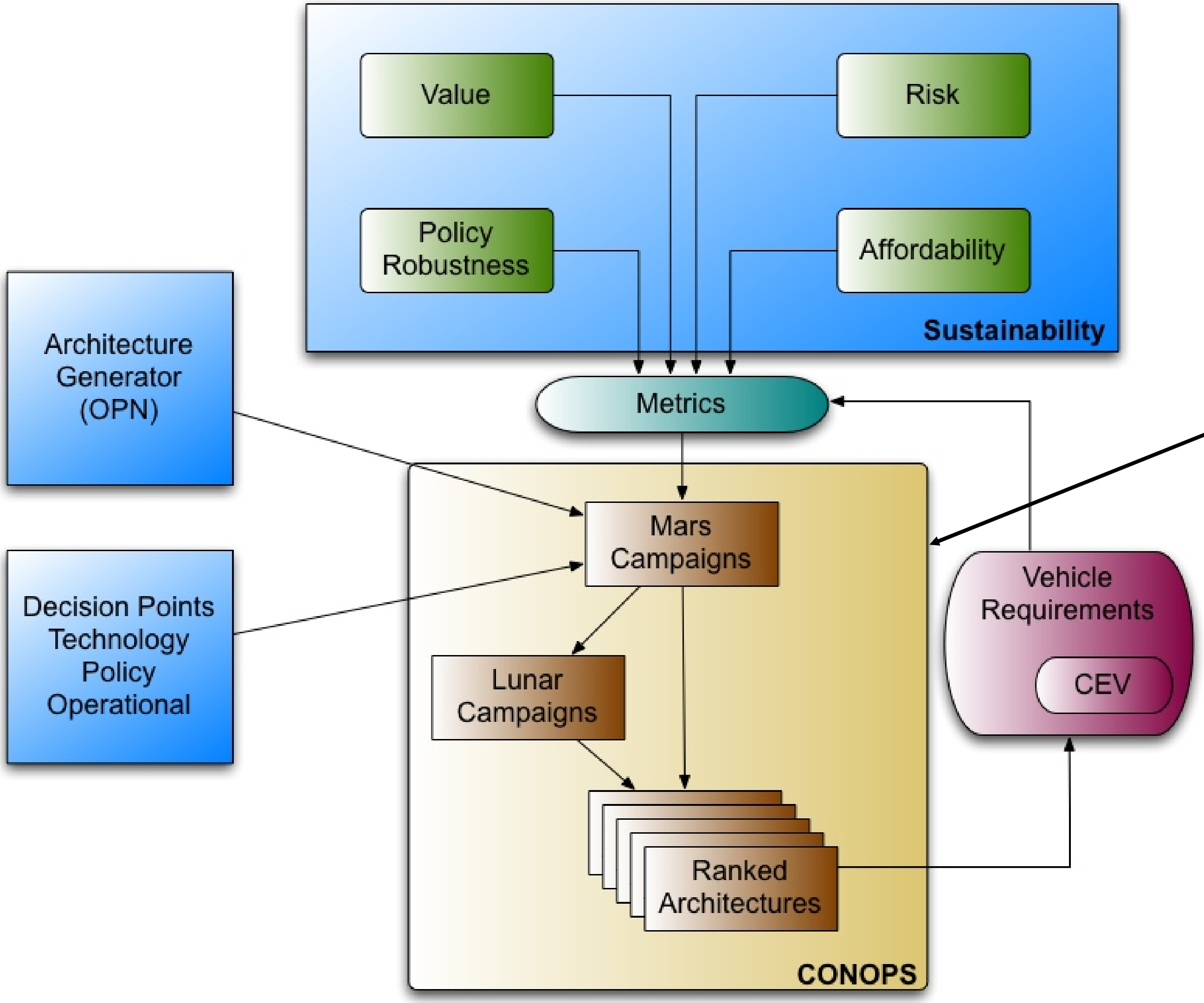
Subsystem Definition

Baseline CEV Concept

Crew Exploration Vehicle Details	
Nominal Crew	4
Endurance	14 days x 4 crew
Pressurized Volume	60 m^3
Habitable Volume	20-30 m^3
Power (average)	5 kW
L/D (bi-conic)	0.6
Total (dry)	*7,500 kg*
Propellant	600 kg
Total (wet)	*8,100 kg*

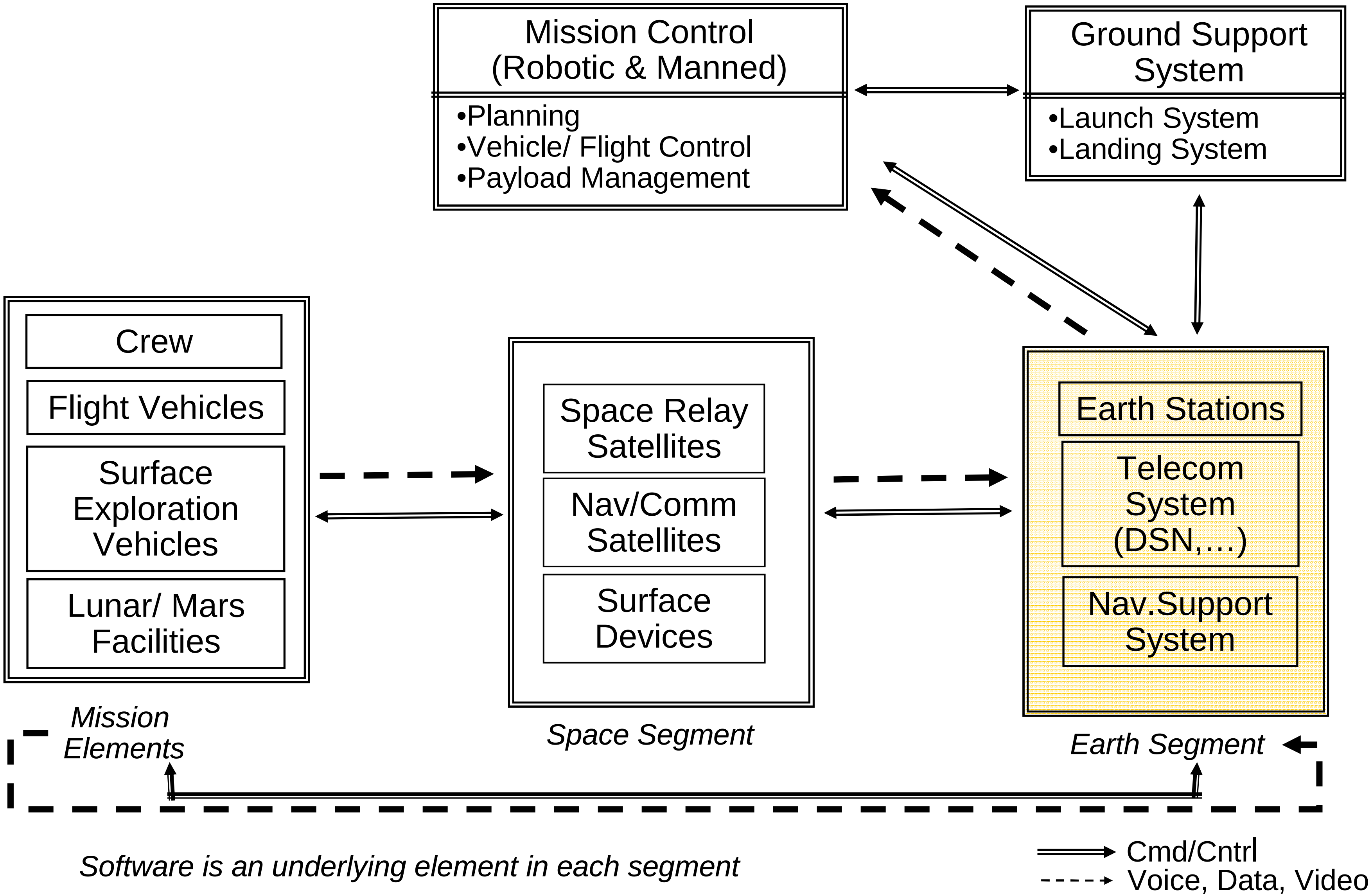


From Requirements to Information System



The data which drives knowledge and therefore value passes through the information system

Information Architecture and Management



Mission Control (Robotic & Manned)
- Planning
- Vehicle/ Flight Control
- Payload Management

Ground Support System
- Launch System
- Landing System

Crew

Flight Vehicles

Surface Exploration Vehicles

Lunar/ Mars Facilities

Mission Elements

Space Relay Satellites

Nav/Comm Satellites

Surface Devices

Space Segment

Earth Stations

Telecom System (DSN,…)

Nav.Support System

Earth Segment

Software is an underlying element in each segment

⟹ Cmd/Cntrl

- - - -→ Voice, Data, Video

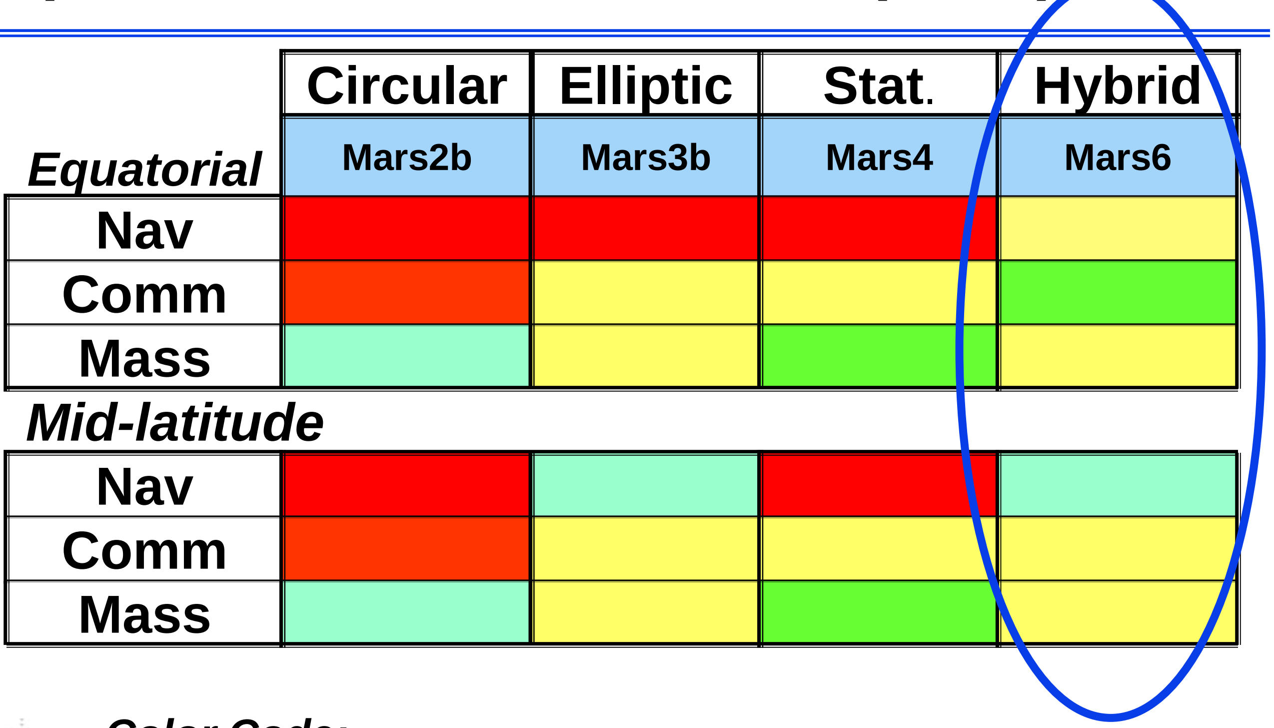
Nav/Comm Metrics

Used three different indicator metrics to rank candidate nav/comm architectures:

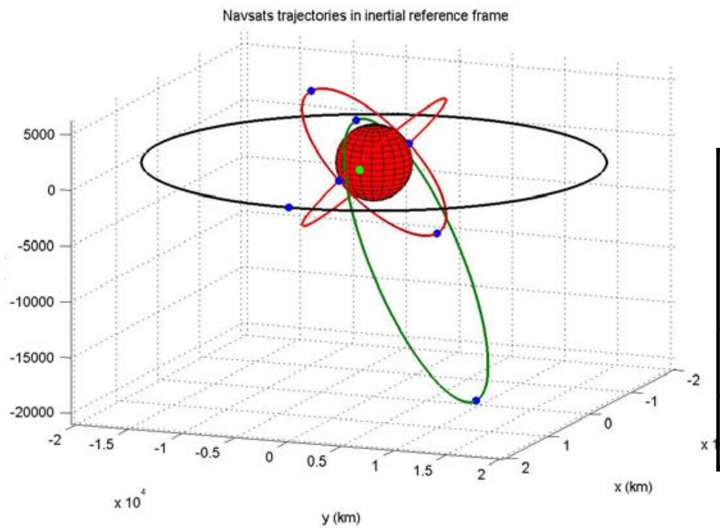
- **Navigation - *Mean Response Time* (MRT): Average time user must wait to obtain good position estimate (defined by DOP < 5). DOP is the quality of user-satellites geometry**
- **Communication - Comm Metric (CM) is the weighed sum of availability, gap time between contacts, and data volume/time/Watt**
- **Mass - Total Mass of satellites in orbit**

Analysis of Representative Architectures (Mars)

Name	*Class*	*# Sats*
Mars1	Onboard	-
Mars2a	Circular	1 (+1L4)
Mars2b		2 (+1L4)
Mars2c		4 (+1L4)
Mars3a	Elliptic	2
Mars3b		4
Mars4	Stationary	1
Mars5	Hybrid	2C+2E
Mars6		3E+1S
Mars7		3C+1S



	Circular	**Elliptic**	**Stat.**	**Hybrid**
Equatorial	**Mars2b**	**Mars3b**	**Mars4**	**Mars6**
Nav	🟥	🟥	🟥	🟨
Comm	🟧	🟨	🟨	🟩
Mass	🟢	🟨	🟩	🟨
Mid-latitude				
Nav	🟥	🟢	🟥	🟢
Comm	🟧	🟨	🟨	🟨
Mass	🟢	🟨	🟩	🟨



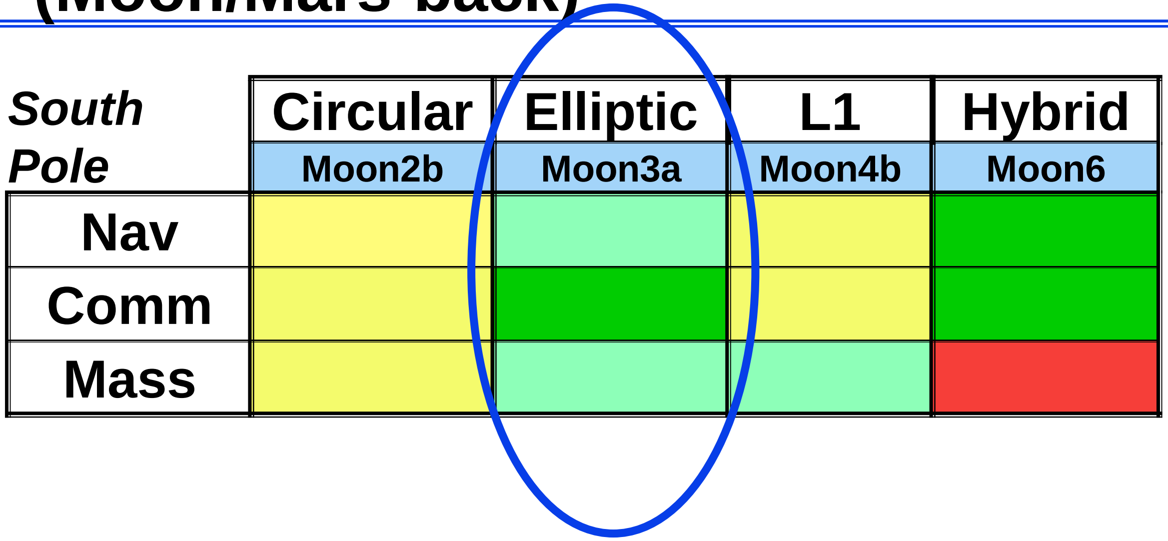
Navsats trajectories in inertial reference frame

Color Code:

Nav	**MRT=0 (Realtime)**	**MRT<~1min (but no realtime)**	**1min<MRT<1 h**	**MRT>1h**
Comm	**CM 5**	**4≤CM≤5**	**3≤CM≤4**	**CM≤2**
Mass	**M<150kg**	**150<M<300**	**300<M<400**	**M>400**

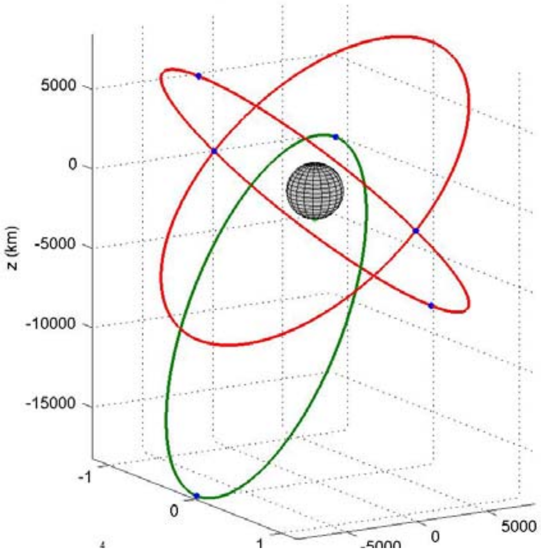
Analysis of Representative Architectures (Moon/Mars-back)

Name	*Class*	*# sats*
Moon1	Onboard	-
Moon2a	Circular	1
Moon2b		4
Moon3a	Elliptic	4
Moon3b		6
Moon4a	L1	1
Moon4b		4
Moon4c		6
Moon5	Hybrid	3C+3E
Moon6		4E+2L1



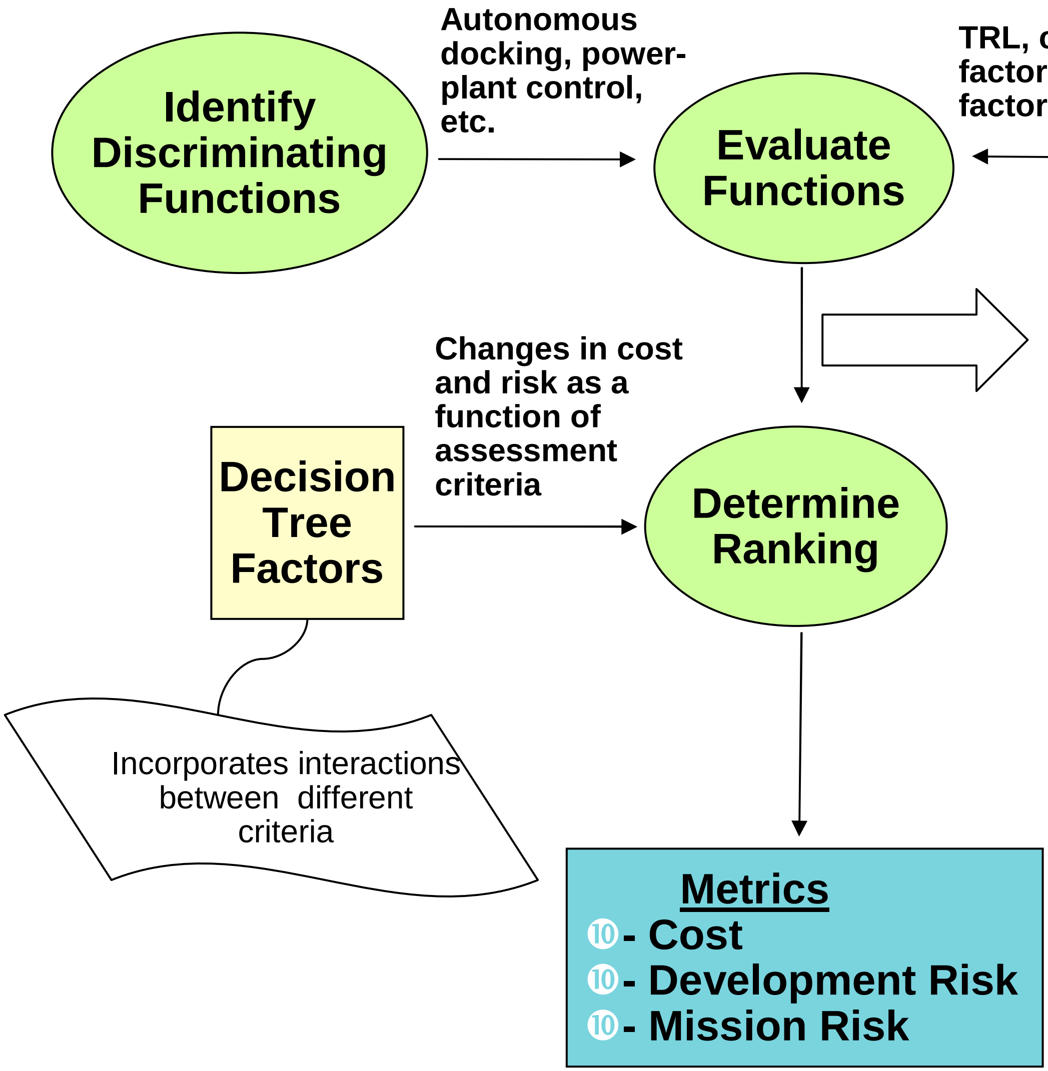
South Pole	**Circular** **Moon2b**	**Elliptic** **Moon3a**	**L1** **Moon4b**	**Hybrid** **Moon6**
Nav	🟨	🟩	🟨	🟩
Comm	🟨	🟩	🟨	🟩
Mass	🟨	🟩	🟩	🟥

Navsats trajectories in inertial reference frame



- **Elliptic orbits provide the best combined performance.**
- **Allows testing of elliptic component of Mars nav/comm architecture during lunar operations.**

Software Tools and Metrics



Identify Discriminating Functions

Autonomous docking, power-plant control, etc.

Evaluate Functions

TRL, complexity factors, human factors, etc.

Assessment Criteria

Changes in cost and risk as a function of assessment criteria

Decision Tree Factors

Determine Ranking

Incorporates interactions between different criteria

Metrics

⑩ - Cost
⑩ - Development Risk
⑩ - Mission Risk

	Autonomous Unmanned docking at L1 between Tugs and OTVs.	Autonomous Unmanned navigation for Tug/OTVs combo (Tug in control).
Are there hard or soft real time constraints?	Yes	Yes
Is a human override or backup function used?	No	No
What type of response is needed by the controller?	N/A	N/A
…	…	…

🟩 Apply to each architecture or function

🟨 Static properties of the method

🟦 Resulting ranking values

Summary

- **A *sustainable* exploration program must focus on delivering value throughout its lifetime to all stakeholders**
  - **We must deliver value, and make all the stakeholders aware that we are delivering value**
- **A Mars-back focus should be maintained throughout the architecture and mission development process**
  - **Increasing credible evidence that design of the system for Mars, and progressive development and deployment on the moon, will only cause minor to modest "suboptimality" for the moon**

Summary - Rationale for Mars via Moon

- Crew must arrive on Mars the first time with a wide variety of assets fully operational: landers, rovers, habitats, power, etc.
- Using moon as development test bed has many systematic advantages:
  - Moon exploration will provide value to many external stakeholders, including scientific, security, commercial and public
  - Can progressively deploy hardware classes to the moon, compatible with available funding, supporting affordability
  - The long preparation time for Mars direct will not yield a string of high visibility events - not policy robust
  - In the event of significant malfunction, crew can be returned from the moon on flexible schedule and quickly, with significant impact on risk

Future Efforts

- Exhaustively examine architectures for surface operations, transportation and information/SW systems, and identify likely system of systems
- Identify key technology/policy/operational decision points, and quantify the impact of the decision on sustainability
- Project requirements from diverse architectures onto CEV to determine requirement robustness
- Systematically examine value delivery system, enterprise architecture based on lean models, and policy robustness of exploration

We want to work with you!