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DECADAL OPPORTUNITIES FOR SPACE ARCHITECTS

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A significant challenge for the new field of space architecture is the dearth of project opportunities. Yet every year more young professionals express interest to enter the field. The paper derives projections that bound the number, type, and range of global development opportunities that may be reasonably expected over the next few decades for human space flight (HSF) systems so those interested in the field can benchmark their goals. Four categories of HSF activity are described: human **Exploration** of solar system bodies; human **Servicing** of space-based assets; large-scale development of space **Resources**; and **Breakout** of self-sustaining human societies into the solar system. A progressive sequence of capabilities for each category starts with its earliest feasible missions and leads toward its full expression. The four sequences are compared in scale, distance from Earth, and readiness. Scenarios hybridize the most synergistic features from the four sequences for comparison to status quo, government-funded HSF program plans. Finally qualitative, decadal, order-of-magnitude estimates are derived for system development needs, and hence opportunities for space architects. Government investment toward human planetary exploration is the weakest generator of space architecture work. Conversely the strongest generator is a combination of three market drivers: (1) commercial passenger travel in low Earth orbit; (2) in parallel, government extension of HSF capability to GEO; both followed by (3) scale-up demonstration of end-to-end solar power satellites in GEO. The rich end of this scale affords space architecture opportunities more diverse, complex, large-scale, and sociologically challenging than traditional exploration vehicle cabins and habitats.

I. INTRODUCTION[1]

Work opportunities for space architects over the past three decades have been concentrated in four domains: Phase A of the International Space Station (ISS), technology programs like TransHab, NASA future-mission concepts, and commercial passenger launch startups. NASA's direction has historically dominated, but the trends bear reexamination. This paper describes the array of project opportunities most likely available to space architects through 2040.

The analysis includes all the spacefaring activities that cannot be done without HSF; derives rational sequences that build from near-term to visionary scale and scope; synthesizes future scenarios by hybridizing the sequences; then compares them for their impact on space architecture opportunities.

The analysis is anchored by four drivers already evident: continuing operation of the ISS, severe NASA outyear budget limitations, increasing difficulty justifying NASA HSF, and nascent commercial space adventure travel.

In prior work[1] the author clarified four options for the purpose of HSF, differentiated as salient by what technology investments they require and by what futures they lead to. Listed in order of increasing numbers of spacefarers enabled after a few decades of $\$10^{10}$/year government investment, the four are: **Explore Mars**, enable **Space Solar Power for Earth**, **Settle the Moon**, and accelerate development of commercial **Space Passenger Travel**. Of the four only the first has motivated HSF government investment throughout the six decades of the field, with the ironic exception of 1961—1972 when HSF was driven by a competitive geopolitical agenda.

The present analysis focuses on in-space HSF activities. Again there are four, mapped to the HSF goals as follows: (1) deep-space servicing and construction (cross-cutting application); (2) exploration (Explore Mars); (3) industrial development of resources (Space Solar Power for Earth); and (4) human "breakout" into space (Space Passenger Travel, and Settle the Moon). From these we can derive potential time-phased project opportunities for space architects.

II. WHY HSF

About 10,000 years ago humans began the large-scale engineering of their world by creating the first works we recognize today as architecture. In the last 100 years, just 1% of humanity's engineering history, a few pioneers envisioned realistic ways to get off the Earth, beyond the atmosphere, and away from the pervasive and fundamental experience of weight. The feat was finally achieved only half a century ago, when the world's population was half what it is now.

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[1] *This work was done as a private venture and not in the author's capacity as an employee of the Jet Propulsion Laboratory, California Institute of Technology.*

The space age is part of what makes us modern. In that same half-century we have visited the deepest seafloor trenches, occupied permanent research stations in Antarctica, built vast airports where there was only sea before, made climbing Earth's highest peaks an adventure sport, networked our collective thinking, and begun reshaping our DNA. Step by step we are expanding the domain of human presence and the very nature of what it means to be human.

Space awaits as an incomparable frontier of human experience: with vistas, sensations, opportunities and risks, and resources and places without limit. Consider what human space flight has accomplished in just its first half-century: proved we can survive off Earth; visited the Moon; brought nations together continuously for a decade in the ISS; and renovated the Hubble Space Telescope several times.

Our robots and telescopes reach much farther than we dare imagine we ever could ourselves. As we learn about our planet, solar system, and universe almost out to the beginning of time, we come to understand the shape of the potential human domain. It ranges from the soils of home to the sands of Mars, and includes thousands of small, weird places as well.

Extending human experience to these limits *is* the sustaining purpose of human space flight. This purpose is neither easy nor quick to achieve, yet it beckons. President Obama has said:

> "Our goal is the capacity for people to work and learn and operate and live safely beyond the Earth for extended periods of time, ultimately in ways that are more sustainable and even indefinite." [2]

These 34 words define a powerful vision that captures four key yardsticks to measure our ambition and progress: making space our home; far from Earth; using what we find there; irreversibly. This open-ended challenge is not fixated on a particular destination, nor is it intended to be the province only of government action; rather it is about humanity stepping outward, to all attainable destinations, forever.

Recognizing that stepping out into the solar system is the underlying goal of our HSF investment can help clarify priorities. Moon and Mars are both meaningful and worthy because they are both eventually attainable. GEO satellite servicing is meaningful and worthy because it offers us the earliest possible human toehold outside the geomagnetic shield. Proposing to step— rather than leap—tempers vision with pragmatism, because it matches the reality of our limited resources.

The most serious sociological challenge to an open-ended vision—one felt by both space advocates and the industrial-political machine—is that there is no urgency discernible in it. Most often this dissatisfaction is formulated as the criticism that NASA has no "clear destination." But naming one would not by itself spark urgency, and the "long view" requires a kind of patience not evident in American culture. The dilemma for space supporters is that those who seek faster progress cannot command the broad popular mandate needed to make it so. In today's world they can neither arrange a significant increase of public investment for an aggressive HSF vision nor sustain it for several decades. And the evidence suggests that neither strident Senate speeches nor op-ed essays can redress this structural mismatch.

For most Americans, non-urgent advancement of HSF capability is a non-issue, but for space supporters it is unpalatable. Noble though it may be, HSF is a "boutique" technology. Electricity, refrigeration, motive power, computers, and networking are technologies that have played a very different role in humanity's progress. They were developed and became ubiquitous because they directly improved the human condition so dramatically that their value was never seriously questioned. However, HSF is seriously challenged to compete with today's other technology frontiers: biotechnology, nanotechnology, clean water, robotics, artificial intelligence, genetic engineering, manufactured food, alternative energy, climate change. Indeed HSF is self-limiting when cast as equivalent to "space exploration;" the farther out it looks, the less relevant it is to urgent considerations. This is a second structural mismatch that cannot be wished away.

Thus a core problem for "why HSF" is: How might stepping out into the solar system be made *central enough to society's needs* throughout the 21st century to stimulate and sustain increased public investment in it?

Antarctica and the continental shelves offer instructive models. Both are destinations analogous to space: remote, alien, risky, and needful of advanced technology. Humanity has stepped out onto Antarctica for routine scientific research without large-scale industrialization (resource extraction is prohibited by treaty) or large-scale living. Is human presence in Antarctica central to civilization? The science done there—paleobiology, geology, extremophiles, climate history, ice-sheet dynamics, atmospheric ozone, astronomy, and meteoritics are just some of the fields—is no less or more important than the science—structure and evolution of the universe, comparative planetology, solar dynamics, history of the solar system, origin and distribution of life—done by exploring space.

Albeit fundamental to modern civilization, science exists only vaguely in the public consciousness. So the level of public investment in science, including space exploration, has found a fairly stable equilibrium within our economy that is unlikely to change significantly. Exploration for the sake of science cannot be the lever HSF advocates seek.

The continental shelves offer a contrasting example. Humanity has stepped out onto the continental shelves, again for exploration and research and—albeit still without permanent settlement—with large-scale industrial operations. The continental shelves are a well explored, well funded, hotly contested, and critical part of both our petroleum energy base and food base. New industries with specialized technologies have been created, political lobbies and controlling interests have emerged, and the associated activities are regulated, taxed, and embedded in modern society. Is human presence on the continental shelves central to civilization? The answer is unequivocally yes.

Could there be an analogous basis for large-scale human activity in space, which is even more remote, risky, and expensive than either Antarctica or the continental shelves? If expanding human presence off the Earth, sustainably and indefinitely, is to be a valid "why"—meaningful enough to motivate sustained or even increased investment—then what could HSF accomplish, and where?

III. WHAT, WHERE

The minimum set of useful things that *only* humans could do, and that could *only* be done in space, contains four types.

Service and Build Assets

Space already contains thousands of high-value assets: satellites for communication, navigation, reconnaissance, and science. Hubble servicing missions have demonstrated the unique value of human space flight for upgrading and repairing systems beyond their designed capacity. Many valuable spacecraft are defunct because of straightforward subsystem failures; and many others are purposely retired before their propellant is exhausted to assure they do not expire in operational orbits.

Today we cannot yet salvage wasted orbiting assets because we cannot get humans into polar orbits, high Earth orbits (HEO), or the geosynchronous belt (GEO). Nor can we service advanced telescopes in Earth-trailing orbits (e.g., Spitzer), at Sun-Earth L2 (e.g., the James Webb Space Telescope currently in development), or at Sun-Earth L1 (e.g., potential synoptic observatories of Earth's day-lit disc).

Beyond maintaining, repairing, and upgrading existing and planned spacecraft, small human crews could assemble spacecraft too large to deploy autonomously. A notable example is assembly of 20–30 m class telescopes. Platforms located at GEO would enable "persistent," high-resolution reconnaissance of any spot on Earth for science or security missions. A large, focusing X-ray telescope would enable revolutionary astrophysics like investigation of the earliest black holes in the universe. Located farther away—whether assembled or deployed there—large optical and infrared telescopes would enable spectroscopy of exoplanet atmospheres, the keystone way to search for signs of life throughout the galaxy.

How essential is HSF for such scenarios? Some advocates of in-space servicing assert advanced robotics could avoid government-dependent, high-orbit HSF, an understandable viewpoint when justifying a business plan to investors. But everyone recognizes that human crews would be quickest and most effective for handling both unforeseen complications and the wide range of configurations and needs posed by servicing and assembling diverse target types.

Servicing and building space-based assets could provide a progressive sequence that extends human presence beyond LEO (Figure 1). In order of increasing challenge and decreasing frequency:

1. Service assets in the three remaining classes of Earth orbit not yet accessible to HSF (polar, HEO, GEO). In different ways these orbits require radiation protection for routine operations. GEO offers the highest-value targets.
2. Construct large GEO optical and/or IR telescopes. This would require weeks-long durations and advanced operations.
3. Construct large optical, IR, UV, or X-ray astronomical telescopes at Earth-Moon L1, a few

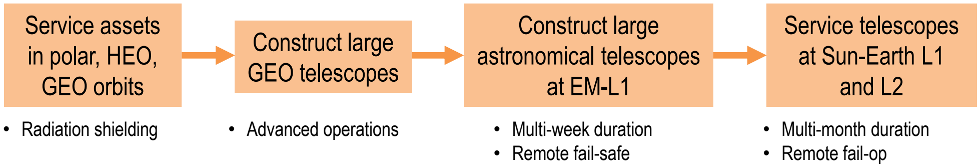

Fig. 1: Progressive Servicing sequence uses HSF to maximize utility of high-value space assets.

days' travel away. Such large telescopes could then be positioned more remotely by electric propulsion for operation.

4. Visit Sun-Earth L1 and L2, with trip times akin to early asteroid exploration, to service telescopes built in step #3 without the multi-year downtime required to cycle them through E-M L1 again using electric propulsion.

Open Space Resources

A special case of assembly and servicing of large space structures is the construction and operation of solar power satellites (SPS) in GEO. Well-studied technically, but not economically viable until it outprices dwindling petroleum supplies, SPS would harvest inexhaustible, continuous, unattenuated solar energy in GEO, convert it to microwaves, transmit it to Earth's surface, and reconvert it into electricity for the terrestrial grid. The beam power density would be safe enough for animals and airplanes to fly through it, and the terrestrial rectenna farms, albeit large in area, would be sparse wire grids superimposed over other land uses like agriculture.

The vision has many skeptics; yet no other apparent combination of in-hand, post-petroleum technologies and land use can maintain the first-world standard of living, raise the rest of humanity on par with it, support hydrogen mobile power, desalinate huge quantities of water, and do these things anywhere on the planet, day and night, sustainably. Conversion to an SPS-based energy economy would signal our graduation from a Kardashev Type-I civilization (utilizing the resources of our planet) into the very first stages of Type-II (utilizing the energy output of our star).

But the SPS alternative is not academic. Demonstrating its end-to-end practicality could be done within the means of existing government space programs. Doing so would prove that civilization's dependence on oil could be broken without disrupting western living standards. Nations that go on to scale it up for full-scale implementation would quickly become major energy exporters, leading to a "state change" in geopolitical balance. Of the spacefaring nations so far, Japan and India have indicated the most serious interest in developing SPS.

Rudimentary calculations reveal the magnitude of space operations required for SPS to make a difference. Today humanity's total power consumption is about 15 TW. To get a sense of scale, assume that in the extreme all of this is supplied from SPS. Further assuming global energy consumption leveled to a first-world standard of living, continued population growth, scaled-up implementation of water desalination, and scaled-up hydrolysis to produce hydrogen for motive power, we should carry a consumption requirement of about 10^2 TW. At 1 AU in free space the power density of solar energy is about 1400 W/m^2. Contemporary but conservative values for photovoltaic conversion efficiency and solid-state transmission efficiency are about 0.3 and 0.8 respectively.[3] So using SPS to provide a reasonable mid-century projection of humanity's energy needs would require roughly 90,000 km^2 of satellites in GEO. For perspective, this is more than 25 times the total paved area of the U.S. federal Interstate Highway System, and about the same area as the state of Maine. Mega-engineering to be sure, this is feasible nonetheless, and more practicable than other post-petroleum schemes—except that it requires space operations.

Proponents point to advances in robotics to assert that in-space construction and maintenance at this scale would not require HSF, perhaps to sidestep yet another advocacy complication. A less extreme view would conceptualize modest onsite human crews supervising—and repairing—fleets of construction and maintenance robots. Again, continental-shelf industrialization is a helpful analogy. The most reasonable scenario would require 10^2–10^3 professional workers in GEO depending on construction rate, who would in turn require dormitory, eating, entertainment, health care, maintenance, and other support services. Opening space energy resources would therefore not just "change the game" for terrestrial energy; it would create several new industries in space.

Energy is by far the most straightforward use of space resources for Earth, because photons have no mass, energy conversion and transmission technologies are well understood, the resource is obtainable close to Earth, and energy on Earth is in great need yet increasingly constrained supply. However, in the distant future material resources from space could conceivably become transformative. High-leverage concepts discussed in the literature for direct terrestrial benefit include platinum-group metals mined from the lunar surface or near-Earth asteroids; and ^{3}He mined from lunar regolith for use in as-yet-unvalidated terrestrial fusion reactors to generate electricity. Concepts posited for in-space benefit include water and other volatiles extracted from lunar deposits or regolith, asteroids, Phobos, or Mars for use as propellant, and construction materials refined and fabricated from Earth Trojan asteroids at Sun-Earth L4 and L5.[4]

Like asset servicing, opening space resources could provide a progressive sequence that expands human presence beyond LEO (Figure 2):

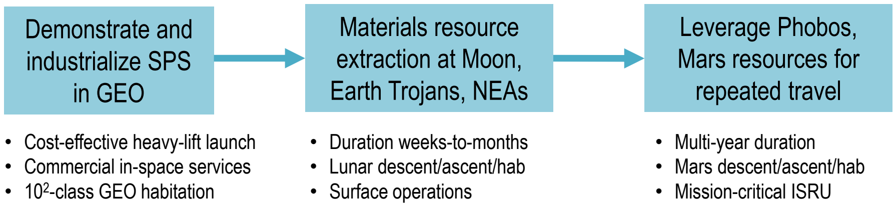

Fig. 2: Progressive Resources sequence industrializes space and increases energetic efficiency of reaching Mars routinely.

1. Conduct SPS scale-up demonstrations in GEO, leading to large-scale industrialization to provide power to Earth.
2. Demonstrate resource extraction and scale-up at the Moon, Earth Trojans, and other energetically favorable near-Earth asteroids (NEAs), leading to expanded deep-space operations.
3. Utilize the volatiles resources of Phobos, and then the surface of Mars, relying on experience gained closer to Earth, for Mars exploration.

Enable the Human Breakout into Space

After fifty years of HSF, about 500 people have traveled in space. That cohort could be increased by orders of magnitude, thereby accelerating the "human breakout into space." Space passenger travel accomplishes the breakout objective of having ordinary people be able to "go."

Space passenger travel for construction and service workers—business passenger travel—is intrinsic to the business case for large-scale SPS as discussed above. However, space passenger travel for the leisure market—space tourism—is different in four fundamental ways: location, duration, amenities, and elasticity. Regarding location, although two salient experiential features of HSF (high acceleration and weightlessness) are common to all HSF, a third is specific to LEO: the incomparable, ever-changing view of Earth. So even if HSF steps out to GEO for industrialization, leisure travel would remain concentrated in LEO. Second, the duration of most leisure travel would be of the same order as terrestrial vacations, between a few days and a few weeks, rather than the months-long tours of duty for GEO construction crews. Third, expectations for amenities would rise with traveler cohort size, which will be inversely proportional to market price. Industrial crews would tolerate more Spartan accommodations as in harsh locations on Earth. Fourth, leisure travel is likely a highly elastic market in which demand is a function of safety first, and flight rate (the principal driver of per-seat price) second.

Early space passenger travel markets are in development now and it is reasonable to project slow market growth. Investment barriers are high for enabling and emplacing the levels of capability needed to access the elastic growth regime. However, government investments in key areas like flight safety, launch system reusability, and orbital system volume and longevity could have significant leverage on growth rate. Advocates for this path envision the space population becoming self-sustaining over time.

Enabling the human breakout into space could also provide a progressive sequence that expands human presence beyond LEO (Figure 3):

1. Commercial enterprise creates leisure destinations and service industries in LEO, increasing HSF capacity and diversifying its capabilities.
2. Governments utilize the commercial LEO capabilities at marginal cost to extend the reach of HSF throughout cis-lunar space and develop lunar surface technologies including resource utilization.
3. Commercial providers leverage the government-funded technologies to extend the reach of passenger travel to lunar orbital cruises and lunar surface excursions.
4. Routine round-trip travel between the Moon and Earth opens the Moon to settlement.
5. A similar public-private cycle establishes trans-lunar free-space settlements at Sun-Earth L4 and L5 if local asteroidal resources are conducive.
6. A similar public-private cycle settles Mars, if one-way travel becomes sociologically acceptable.

Explore New Environments and Faraway Places

The fourth HSF activity would seek to explore all the places that can be reached with human crews. Beyond LEO this has traditionally meant simply the Moon and Mars, although NEAs have recently become admissible as intermediate destinations. To complete the set we could include late-21st-century, decadal-duration human missions into the main asteroid belt where

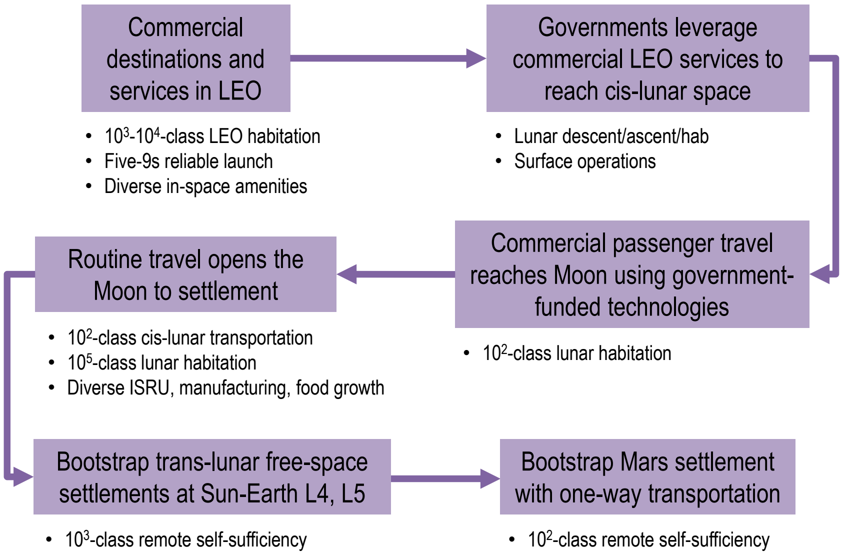

Fig. 3: Progressive Breakout sequence establishes full-fledged human societies in space.

thousands of unique worlds await, using the solutions to space radiation, life-support, and propulsion that would have been developed for Mars-class missions. All other natural destinations in our solar system—Venus, Mercury, the outer planets and their moons, and probably the trans-belt small-body populations—are either too inimical or too remote, or both, for human exploration to be reasonably foreseeable with technologies we know and risks we could manage.

Directly bringing human capacities for observation, cognition, interpretation, experience, dexterity, and adaptive behavior to faraway places has always yielded incomparably rich exploration. Project Apollo proved that human space exploration has the potential to be globally historic and scientifically valid. While we can argue whether more extensive exploration of the Moon, or exploration of deep-space asteroids, could match that sociological and scientific benchmark, humans exploring Mars would. Human exploration of Mars may be essential for definitively concluding the epochal investigation of whether Mars ever supported life, whether it still does in protected places, and if so whether that life shares the same chemical basis as life on Earth.

Direct human exploration of natural bodies in space outlines the "traditional" progressive sequence to expand human presence beyond LEO (Figure 4):

1. Mount expeditions to the nearest visible destination, the Moon. *Of the four sequences described in this analysis, this is the only step that has been taken so far, by Apollo.*
2. Return to the Moon, with methodical lunar exploration that increases staytime to months and takes crews to regions invisible from Earth.
3. Mount expeditions to deep-space destinations that cannot be seen easily but are within ~1-yr travel (NEAs).
4. Use a sequence of confidence-building missions to NEAs that incrementally increase duration and distance, culminating with Phobos at Mars.
5. Mount surface expeditions at Mars, with staytimes ranging from opposition-class (~1 month) to conjunction-class (2 years).
6. Sustain continuous presence on Mars with rotating crews, if thorough exploration of the planet requires HSF over the long term.
7. Mount multi-year expeditions into the main asteroid belt.

IV. RATIONAL CAPABILITY SEQUENCES

All four activity sequences would expand human presence into the solar system if implemented, but none of them alone is likely to justify or cause the expansion (Figure 5). Each has strengths and weaknesses.

The Exploration sequence offers a way for governments to work together peacefully developing advanced technology; but supports only a thin, possibly sporadic series of missions because it cannot occur near Earth yet getting away from Earth requires enormous—even global—investment for every mission. The Breakout sequence offers direct public relevance, an elastic LEO "onramp" already moving forward, and a way for governments to avoid developing their own HSF

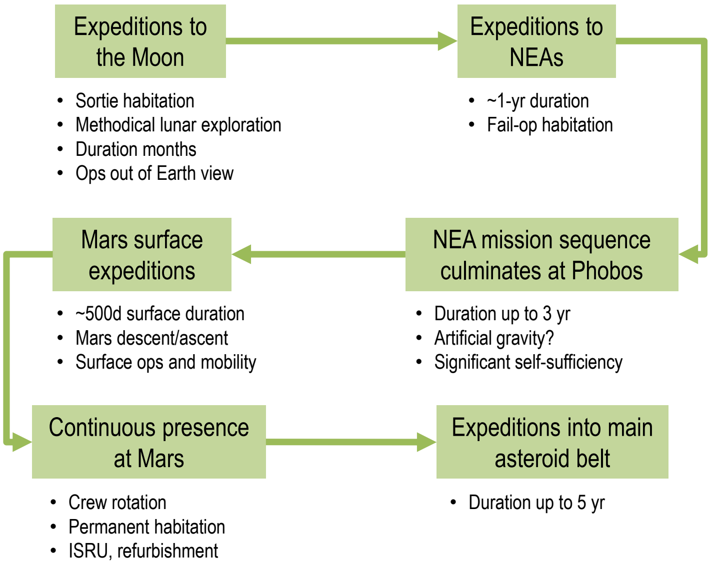

Fig. 4: Progressive Exploration sequence extends direct human presence as far as possible. The first two steps can arguably be taken in either order.

logistics tail; but farther out it faces technical barriers to feasibility that can be surmounted only with government investment. The Resources sequence offers an elastic path to large-scale space industrialization because it would create a pyramidal economic structure of public-private partnership to feed modern energy appetites indefinitely; but beyond GEO it becomes brittle, speculatively dependent on either large-scale lunar mining operations or non-terrestrial markets that would value materials in situ. The Servicing sequence has the lowest barrier to entry from the current state but becomes extremely thin beyond GEO because even in the best case there would be only a few large, long-lived deep-space astronomical facilities to service.

However, the four activity types are not mutually exclusive, and promising scenarios can be constructed from the best features of each. Figure 6 shows how steps from multiple sequences might be combined. Best understood as a precedence diagram (i.e., read from right to left) it shows that Settlement goals at various destinations would be enabled (necessarily but not sufficiently) both by government-developed technologies and by space resource development. Choices about which resources to develop are constrained by a fundamental government choice between two tracks: one leading through NEA missions to Mars and beyond; or one leading toward settlement of the lunar surface.

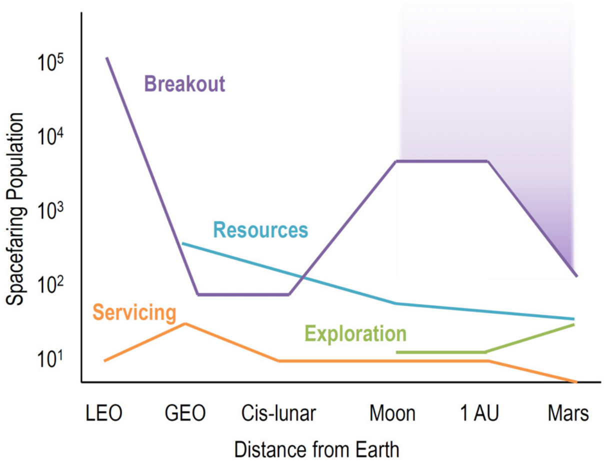

Fig. 5: Spacefaring population potential vs. destination class varies significantly among alternative post-ISS HSF activity sequences. Color code is common with Figs. 1–4.

It is financially unrealistic to expect government HSF investment to enable both paths even though they interconnect on the diagram. The Mars (upper) path implements multiple, progressively-distant missions and begins with the currently-stated USG goal of a human NEA mission. The lunar (lower) path uses commercial infrastructure to minimize development and operations costs, and begins with the objective stated by today’s commercial orbital transportation players: selling LEO services to the government. Alternative diagrams are of course possible, for example a NEA-Mars sequence could be designed to leverage commercial LEO services. But because of the high cost barrier, government investment faces a stark choice between divergent goals: the lunar path leads toward bringing the Moon within the economic and

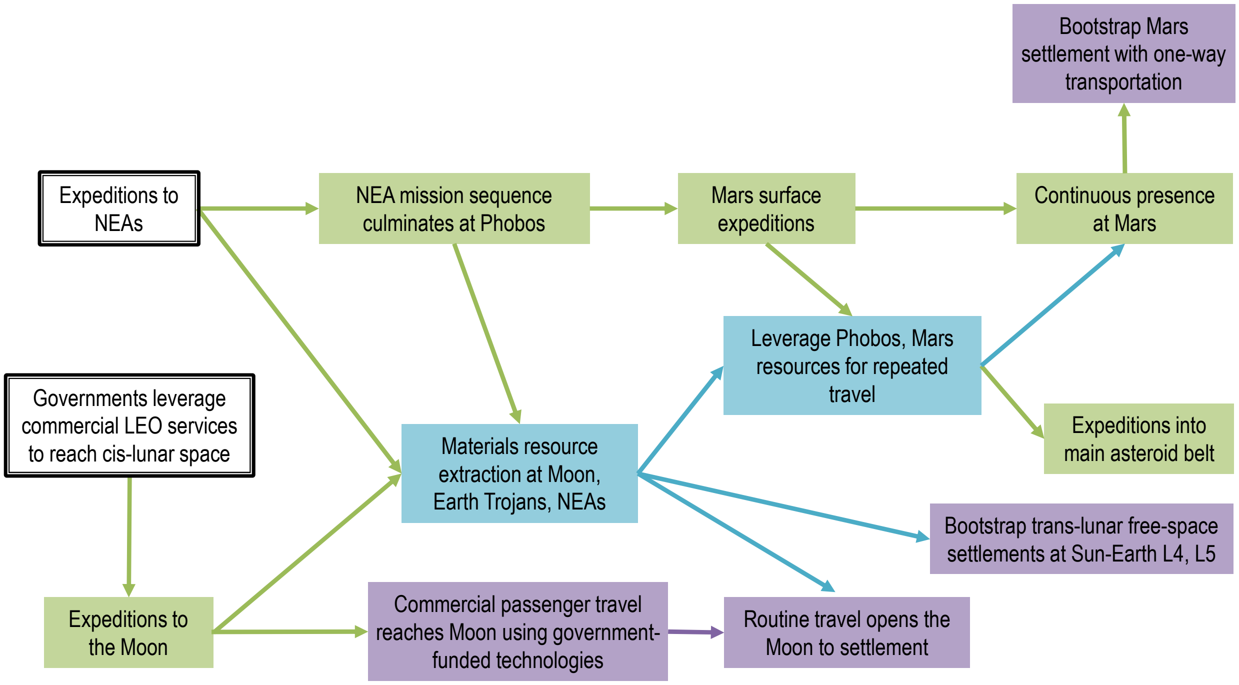

Fig. 6: Hybrid sequences create rational scenarios. Vision-reining costs force a choice for government investment between Exploration and Settlement goals.

sociological sphere of the Earth, while the NEA-Mars path leads toward more distant places with a lesser number of humans.

Strangely, given the persistently vehement debate about it, this critical choice can be deferred because today's issue is how to get going on any roadmap at all. Overcoming the high barrier to entry for HSF beyond LEO is the core government-HSF challenge of the next two decades. Constellation showed that realistic levels of USG investment alone could not attain lunar sorties, let alone open-ended surface operations. Neither can USG investment alone achieve even a first NEA mission within a politically acceptable time, as shown by recent HEFT (Human Exploration Framework Team) and HAT (Human Exploration Architecture Team) analyses.[5]

Figure 7 shows a scenario that breaks through this problem. First, the Servicing sequence offers an incremental way for the USG to get humans beyond LEO. Demonstrating the practicality of recycling high-value space assets is a legitimate purpose for HSF. It has already been done to great effect in LEO, and affordable investments beyond various combinations of existing and contemplated space transportation systems could extend it to other Earth orbits. GEO in particular offers diverse servicing challenges, nearby experience outside the geomagnetic shield, and a way for HSF to validate or assist entrepreneurial robotic servicing startups. GEO operations experience would then enable more complex activities like building large telescopes (for Earth science, for surveillance, and/or for astronomy) and demonstration of SPS.

Early end-to-end SPS technology demonstrations at GEO distance would not require HSF, but deployment demonstrations to validate scale-up assumptions would. The HSF experience gained would prove useful even if space-based power fails to gain traction as a viable terrestrial energy option. And if it does, the dashed line indicates that subsequent HSF roadmaps would become fundamentally shaped by the capabilities its full-scale implementation would emplace: very high-capacity, high-rate, heavy-lift launch; large numbers of GEO workers; advanced robotics; and essentially unlimited in-space power.

Again, other scenarios are feasible. For example USG mission architectures to reach and operate at GEO or even EM-L1 could leverage commercial LEO services, thereby avoiding unique system developments, accelerating schedule and boosting commercial business.

Strategically hybridized scenarios hold more promise for bootstrapping HSF beyond LEO than does the "pure" sequence of destination-driven USG missions (Figure 4) persistently proposed by NASA planning teams. Four strategic levers appear to differentiate "rich" from "impoverished" HSF futures:

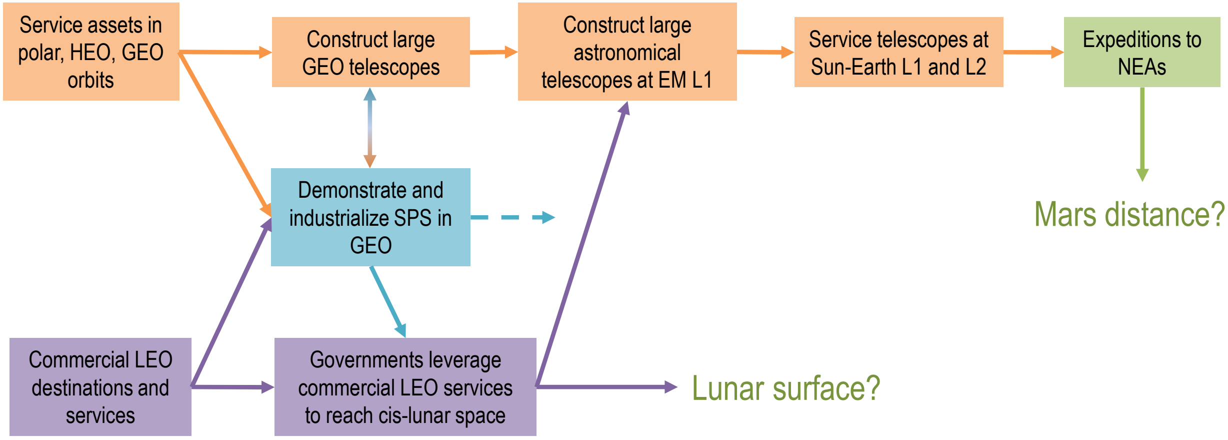

Fig. 7: Potential startup scenario outlines a pragmatic onramp to the futures in Figure 6. Government "destination" decision between investing in lunar surface operations or deep-space NEA/Mars missions is deferred until beyond-LEO progress is demonstrated on clearly useful missions.

1. Move away from the specious conceptual constraint that USG HSF must always be about Exploration. Other HSF objectives worthy of USG investment provide more feasible onramps.
2. Focus first on GEO as a versatile, beyond-LEO location to demonstrate capabilities useful to multiple possible futures.
3. Implement architectures that leverage commercial LEO capabilities to the maximum possible degree: launch, orbit transfer, habitation, and eventually labor. Use USG investment for technologies that lower the bar for commercial providers (e.g., high-reliability launch, reusability, in-space habitat assembly) rather than to develop unique all-in systems (e.g., launch vehicles) as in NASA's past.
4. Defer programmatic commitment to either the Exploration or Settlement paths until SPS has been demonstrated—it might change everything.

V. SPACE ARCHITECTURE REQUIREMENTS FLOWDOWN

Potential opportunities for space architects over the next half century can be derived from this analytical foundation. How optimistic could—or should—our profession be, and what informed advice can we provide to hopeful young professionals seeking to enter our field?

Pacing constraints are:

1. Strategic flexibility of government space programs (particularly the best-funded ones, NASA and CNSA) in choosing investment objectives other than planetary targets
2. Resource allocations to and by those space programs
3. Private capital applied to entrepreneurial space endeavors
4. Disruptive "wild cards" that cannot be predicted, including economic and geopolitical shifts; technological progress in relevant domains; HSF accidents; and evolving sociological norms.

As a bounding case Table 1 details a "fast-onramp" future adapted from Figure 7 and leading to the "rich" future of Figure 6. Predictive resolution is limited to decadal time intervals and order-of-magnitude spacefaring populations.

Repeated HSF GEO servicing missions could be underway by 2020. With in-hand technologies large telescopes could be constructed by the mid-2020s, and SPS scale-up demonstrations could be conducted by 2030. COTS (commercial orbital transportation service) providers would partner with entrepreneurial habitation providers to expand boutique tourism from suborbital rides to continuous multi-day orbital stays and occasional cis-lunar excursions for the very rich by 2030. By that time Mars habitability would have been characterized by NASA and ESA robotic science missions, positioning governments to choose among the HSF pathways: toward Mars exploration, toward lunar settlement, or toward industrial exploitation of space power in GEO. The final column of Table 1 indicates, using terms familiar from terrestrial applications, the types of space architecture needed to meet these needs.

Decade	Location	Function	Capacity x Frequency	Duration	System Class
2010s	Earth – LEO	Access/ return	10^1 passengers x 10^1 trips/yr	Days	**Small-plane-size cabin** in reusable launch/entry vehicle
	LEO-GEO	Orbit transfer	10^0 crew x 10^0 trips/yr	Days	Short-duration **deep-space cabin** on in-space tug, possibly reusable
	GEO	EVA/EVR operations	10^0 crew	Hours total	Telerobotics stations/tools, **airlock/spacesuit**
2020s	LEO	Orbit transfer	10^1 tourists + 10^0 crew x 10^1 trips/yr	Days	**Short-duration LEO bus** for tour excursions around and among orbital destinations
		Habitation	10^1 tourists	Days-weeks	**Cabins**, dual/quad occupancy **Long-life hostel** facility (mess, observation, clinic)
			10^1 staff	Months	Long-life a**partments** **Health clinic**
	Cis-lunar	Orbit transfer	10^0 tourists + 10^0 crew	Days	**Deep-space cabin** for high-end tour excursions, possibly reusable
			10^1 crew x 10^0 trips/yr	Weeks	Deep-space **living/work trailer**, one-time or intermittent use
		EVA/EVR operations	10^1 x 10^0 trips/yr	Days total	**Routine, quick-egress EVA** (e.g., suitport, man-in-can)
2030s w/o SPS	Earth – LEO	Access/ return	10^3 passengers/yr	Hours	**Commuter-jet-size cabin** in reusable launch/entry vehicle
	LEO	Habitation	10^2 tourists	Days	**Dual-occupancy staterooms** **Outfitted hotel** including assembly spaces (lobby, bar, diner, restaurant, theater, ballroom, spa/gym, infirmary)
			10^2 staff	Months	**Dormitory** + hotel facilities
	Cis-lunar	Orbit transfer	10^1 tourists + 10^0 crew x 10^1 trips/yr	Days	**Dual-occupancy staterooms in small deep-space cruise ship** for excursion tours
			10^0 crew x 10^0 trips/yr	Days-weeks	Deep-space **living/work trailer**, infirmary, intermittent use
	Lunar surface or trans-lunar	Exploration operations	10^0 crew x 10^0 trips total	Weeks-years	Developmental **campsites** (applications laboratory, habitable rovers, airlock/suit, food growth, surgery-capable infirmary), intermittent use
2030s w/ SPS	Earth – GEO	Access/ return	10^2 workers/yr	Hours	**Commuter-jet-size cabin** in reusable launch-GEO-entry vehicle
	GEO	Orbit transfer	10^1 workers	Continuous use	Reusable **commuter bus** between worksites and habitat
		Habitation	10^1 tourists	Days	**Cabins**, dual/quad occupancy **Long-life hostel** facility (mess, observation, infirmary)
			10^1 staff	Months	Long-life a**partments** Hostel facilities + gym
			10^2 workers + 10^1 – 10^2 operations staff	Months	**Dormitory** **Assembly/recreation spaces** (bar, mess, theater, gym, surgery-capable infirmary)
		EVA/EVR operations	10^2 workers	Continuous	**Routine, quick-egress EVA** (e.g., suitport, man-in-can)

Table 1: Hybrid on-ramp scenario bounds the types of space architecture that may be commissioned out to ~2040. Industrialization of GEO for SPS is the most significant wild card.

This scenario has profound implications for space architects:

1. Significant opportunities to begin developing planet-surface space architecture do not emerge until at least the 2020s.
2. In-space habitation needs through the 2020s can be met by systems with capacity of tens of people.
3. Transportation systems to and from orbit need not carry more than tens of people until at least the 2030s.
4. Commercial passenger travel in LEO dominates government exploration as a driver for both the number and diversity of space-architecture systems. Competitive granularity (multiple competitors and parsed customer demographics) proliferate the space architecture opportunities within this market even more than the table implies directly.
5. Orbital passenger travel even in the 2020s requires architecture solutions for non-professionals on short stays, for professional staff for long stays, and for recreation, life support, and food appropriate for paying non-professionals.
6. A decision by one or more governments to invest in SPS rather than HSF exploration significantly augments the market need for space architecture: quantitatively (capacity and duration), qualitatively (traffic directly to and from GEO), and demographically (workers in addition to tourists and staff).
7. Habitation solutions for thousands of tourists per year in LEO may be adaptable into solutions for hundreds of SPS construction workers and support staff continuously in GEO.

Using the spacefaring human-factors model proposed by Sherwood and Harrison[6] the space architecture "frontier" can be mapped in time (Figure 8). Today the primary space architecture needs are immediately physical for small, professional crews. The 2020s sees this same set of challenges expand to passengers. Crew psychology does not evolve significantly because even multi-week trips into cis-lunar space are filled with task-directed activity. By the 2030s passenger psychology begins to shift away from sheer adventure and toward richer accommodation, crew psychology begins to reflect the reality of staff hired for partial-year tours of duty, and the number of simultaneous tourists introduces sociological considerations. Again the wild card in the 2030s is SPS industrialization, which would add the dimension of (construction) crew sociology due to large numbers of spacefarers.

Today	Mission Crews	Passengers	Settlers
Ergonomic	■		
Biological	■		
Psychological	▨		
Sociological			

2020s	Mission Crews	Passengers	Settlers
Ergonomic	■	■	
Biological	■	■	
Psychological	▨	▨	
Sociological			

2030s w/o SPS	Mission Crews	Passengers	Settlers
Ergonomic	■	■	
Biological	■	■	
Psychological	■	■	
Sociological		■	

2030s w/ SPS	Mission Crews	Passengers	Settlers
Ergonomic	■	■	
Biological	■	■	
Psychological	■	■	
Sociological	■	■	

Fig. 8: Evolving market will call for space architecture to solve increasingly sophisticated challenges driven by spacefarer type, group size, flight duration, and distance from Earth. No reasonable scenario requires development of "settler" solutions by 2030. Darker cells indicate full need.

VI. CONCLUSION

Meaningful work for space architects will occur in direct proportion to the vibrancy of development of habitable space flight systems. The opportunity parameters that matter most to practicing or hopeful space architects are immediacy, number, and diversity. The evolutionary HSF sequence that maximizes these parameters leverages three enabling markets: (1) commercial orbital passenger travel leading to LEO hotels and (2) parallel government expansion of HSF capability from LEO into GEO, both followed by (3) demonstration of end-to-end SPS to inform decisions by governments and energy investors regarding implementation scale-up. Government investment in HSF exploration capability yields significantly fewer and less diverse opportunities for space architects over the decadal timescales of their working careers.

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