Modular, Reconfigurable, High-Energy Systems Stepping Stones

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Abstract

Modular, Reconfigurable, High-Energy (MRHE) Systems are stepping stones to provide capabilities for energy-rich infrastructure strategically located in space to support a variety of exploration scenarios. Abundant renewable energy at lunar or Earth-Moon Libration (e.g., "L1") locations could support propellant production and storage in refueling scenarios that enable affordable exploration. Renewable energy platforms in geostationary Earth orbit (GEO) can collect and transmit power to satellites, or to Earth-surface locations. Energy-rich space technologies also enable the use of electric-powered propulsion systems that could efficiently deliver cargo and exploration facilities to remote locations. A first step to an energy-rich space infrastructure is a 100-kWe class solar-powered platform in Earth orbit. The platform would utilize advanced technologies in solar power collection and generation, power management and distribution, thermal management, and electric propulsion. It would also provide a power-rich free-flying platform to demonstrate in space a portfolio of technology flight experiments.

This paper discusses the reasons why such advances are important to future affordable and sustainable operations in space. It also presents preliminary concepts for a 100-kWe solar-powered satellite with the capability to flight-demonstrate a variety of payload experiments and to utilize electric propulsion. State-of-the-art solar concentrators, highly efficient multi-junction solar cells, integrated thermal management on the arrays, and innovative deployable structure design and packaging make the 100-kW satellite feasible for launch on one existing launch vehicle. Higher voltage arrays and power management and distribution (PMAD) systems reduce or eliminate the need for massive power converters, and could enable direct-drive of high-voltage solar electric thrusters.

An Affordability Challenge

One of the central barriers to more ambitious—yet still affordable—space operations in the Earth's neighborhood lies in our inability to affordably preposition consumables (particularly propellants) and needed systems (including spares for in space servicing and maintenance). As long as it is not possible to locally repair and refuel high-value (and high-cost) space systems beyond low Earth orbit (LEO). This challenge affects planning for a wide range of potential future missions, but is particularly important for (a) major, high-value missions such as human exploration activities beyond low Earth orbit; (b) large-scale defense and/or security focused mission systems; or, (c) 'future space industries' (such as larger, multi-payload geostationary Earth orbit (GEO) platforms, space solar power systems, and related concepts).

For example, a large-scale, permanently inhabited lunar base might involve 3-4 human missions to the Moon per year (for crew rotation every 120 days or 90 days, respectively). However, if such a mission scenario were to involve Apollo-era concepts and current-technology expendable space transportation systems, then the total cost per mission due to transportation costs alone (hardware and operations), could range from $2,400M per mission to more than $3,100M per mission (current year dollars). Transportation cost components here are assumed to include the following:

- ETO Transport: Assuming Shuttle-derived, expendable systems involving 2 Heavy Lift Launch Vehicles (HLLVs), 1 Crew Launcher at a total cost of $500M to $1,000M per mission. Note that this rough estimate for ETO costs is intended to be comparable to (but lower than) the Space Shuttle at about 3-4 launches per year, plus typical EELV (evolved expendable launch vehicles) costs per launch at the same rate.
- In Space Transport: Assuming expendable systems involving at least two in-space stages with individual mass of about 10,000 kg (and a recurring unit per kilogram cost of about $50,000 per kilogram[1]) for a "per mission cost" of about $500M per mission.
- Excursion Transport: Assuming expendable systems, involving nominally a descent module and an ascent module with a combined mass of about 10,000 kg to 20,000 kg (and a recurring unit per kilogram cost of approximately $50,000 per kilogram), for a "per mission cost" of about $750M per mission.
- Transportation Operations. Assuming incremental improvements on Space Shuttle and International Space Station (ISS) era ground operations concepts,, involving nominally about 20,000 total personnel (with an average cost of about $100,000 per FTE[2] (full time equivalent)), for a "program per year cost" of about $2,000M, and a per mission cost of about $500M per mission at a rate of 4 missions per year, or about to $667M per mission at a rate of 3 missions per year.

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[1] The very rough, mass-based cost estimation relationships (CERs) used in this illustration are intended to be consistent with—and perhaps a bit on the optimistic side of—past human-rated space systems recurring hardware costs. A more detailed analysis would consider the specific cost per kilogram for each of the major elements in each system, as well as taking into account the specific number of unique elements to be manufactured over the life of the program, and the degree to which advanced production methods (such lean manufacturing) might be brought to bear on the problem. However, for the purposes of this discussion, the single value of 'about $50,000 per kilogram (about $22,000 per pound) for recurring flight hardware costs seems adequate.

[2] This figure is intended to be a very rough average, integrating all personnel involved; clearly some cost categories, such as senior engineers, are at much higher labor rates when 'fully wrapped'.

In summary, this scenario would result in an annual cost—for lunar base transportation only—of approximately $7,000M/year (best case, 3 missions/year), to about $11,000M/year (worst case, 4 missions per year). Additional costs would, of course be incurred for crew transportation systems, supporting infrastructures (such as communications systems), as well as for the wide range of surface systems that would be needed for a lunar base. (It is perhaps worth noting that in the case of the tightly interwoven Space Shuttle and ISS programs, the costs of transportation to and from the Station are very roughly equivalent to the costs of ISS engineering and operations. If the same were to hold true for a far-more technically challenging lunar base and its transportation system, then the total annual costs would be double the figures noted above—or equivalent something greater than the entire current U.S. annual civil space budget.) The total of such annual operational costs would, of course, far exceed the current annual US investment in human space flight. Moreover, they would not allow for vitally needed investments in the systems that would allow us to go beyond and initial operational base.

Although the sketch above is specific to a notional lunar base, the affordability issues involved are quite similar for a range of other ambitious future space operational scenarios— particularly those involving (as does the Terrestrial Planet Imager (TPI) concept) a number of exceptionally large, high-value imaging systems deployed beyond low Earth orbit (LEO).

A Notional Solution

One potential solution to this challenge is to move successfully to more affordable reusable space transportation system elements with substantially higher levels of onboard autonomy. Four functional challenges must be resolved to enable this highly desirable, but technical difficult transition:

- Lower cost ETO transport (perhaps by enabling a transition to launchers that are more similar to those used by other government organizations or by commercial sectors; and in the long term by transitioning to reusable launch vehicles);
- Highly-autonomous assembly, maintenance and servicing of modular systems in space and on planetary surfaces (including both robotic and crew-assisted operations),
- Affordable and timely pre-positioning of fuel, systems and other materiel throughout the Earth-Moon system (including to the surface of the Moon); and,
- Reusable, highly reliable and high-energy in space transportation (and for lunar missions, excursion transportation systems).

The systems that would enable such visionary capabilities must also be highly autonomous (to reduce ground operations costs), as well as substantially less expensive to buy and own (with greater operational margins than current systems, as well as lower per unit costs—perhaps achieved through modularity and the economies of production).

Detailed studies would be needed to determine the appropriate technical performance objectives for such advanced systems—in the context of cost constraints and reliability (safety) goals. However, it seems plausible to suggest that at a minimum, such future R&D efforts should target new systems approaches and novel technologies that would make possible not less that a factor of four reduction in per mission costs, and perhaps as much as a 10-fold reduction. In the case of the lunar base example sketched above, a 4-fold reduction would be equivalent to seeking to achieve a lunar base per mission transportation cost of no more than $1,750M to $2,750M per mission—or, in the case of a 10-fold reduction, a per mission transportation cost of no more than $700M to $1,100M per mission. (For comparison, note that the latter figures are roughly comparable to the fully-loaded costs of Space Shuttle missions to LEO at the present time—although they are still much greater than the marginal costs of such flights.)

However, setting a goal is hardly the same as achieving it. Although the technologies needed to achieve this vision are (in many cases) already validated in the laboratory, they are certainly not 'in hand' or sufficiently mature to incorporate into space systems being build today. As a result, substantial research and technology development and validation must still be undertaken in order to realize the potential cost savings that are so clearly needed in end-to-end space transportation.

Fortunately, the capabilities for local refueling, as well as locally autonomous assembly, repair and maintenance are inherent for any kind of extended and ambitious deep space scenario—such as a lunar surface base.[3] Moreover, they become even more critical as one considers the long-term requirements of human mission to Mars, much less the far more ambitious requirements of extended human presence and activity in space (e.g., space settlements or missions beyond the inner solar system). As a result, the future development of such technologies should be broadly beneficial to the full range of ambitious mission options that are under consideration by various organizations.

Key Technical Challenges

The central functional issues associated with affordably realizing advanced, highly reusable architectural concepts lies in solving several key technology challenges. These include:

- Tele-supervised (and eventually autonomous) highly resilient deep space systems operations (in this case, 'deep space' operations includes all ambitious mission operations beyond LEO).
- Reconfigurable and self-adaptive modular systems.
- Space assembly, maintenance and servicing (from the systems level, down to the subsystem level).
- Highly fuel-efficient, high reliability, re-startable propulsion, such as high-power electric propulsion for cargo and cryogenic engines for time critical mission (such as those involving astronaut crews).
- High-energy propellants for long-duration missions (particularly cryogenic propellants such as liquid oxygen, liquid hydrogen, etc.)
- Long-term storage and management, as well as the highly reliable and low-loss transfer (including transfer in micro-gravity) of cryogenic propellants.
- High-power, but low-mass space power generation and management systems

This paper will deal with a specific class of these technology problems: in particular, those that involve affordable, high-efficiency in-space transport of logistics

[3] Note: although smaller missions—such as those involving traditional communications satellites—might benefit from in-space refueling, low-cost in space transportation and similar space operations, the costs of developing and deploying such transformational new capabilities are difficult, if not impossible to justify based on these missions alone.

using modular, reconfigurable high-energy systems.

A Novel Concept: MRHE

Modular, reconfigurable high-energy (MRHE) systems are one novel conceptual approach with the potential to meet the challenge of enabling affordable pre-positioning of key logistics (including fuel, hardware, and appropriate systems) to points beyond LEO. An MRHE system is an integrated, high power, solar electric propulsion (SEP) vehicle that provides high fuel efficiency from LEO to destinations throughout the Earth-Moon system (including MEO, GEO, low lunar orbit (LLO) and Sun-Earth Lagrange points).

The MRHE concept consists of identical solar-powered modules, each equipped with an electric propulsion system, assembled in a reconfigurable arrangement that supports power generation redundancy and engine-out capabilities. For example, a promising MRHE approach is a linear configuration such as that illustrated in Figure 1 (shown in a gravity gradient stabilized mode). Alternatively, a tetrahedral configuration has also been examined, such as that illustrated in Figure 2.

Figure 3 illustrates respectively the full system and a in a normal-to-the-orbit-plane configuration. And Figure 4 illustrates a typical self-assembly sequence for an MRHE.

In any case, the MRHE concept provides for payload attachments on each module to provide flexibility and re-configurability options for accommodating multiple technology experiments and eventually different exploration payloads. In the case of a linear configuration, the platform may also provide a single, larger payload attachment at the central of gravity of the integrated vehicle.

However, at this time MRHE systems entail considerably greater system development uncertainty than more conventional systems and technologies (e.g., fully expendable, Apollo-era concepts with technologies that are already at a flight-like technology readiness level—i.e., TRL 7-9). As a result, significant R&D investments are needed prior to beginning major systems development. However, if affordability and sustainability are important characteristics for future transformational space operations, then the development of new technologies and capability is essential. MRHE systems (or equivalent alternate approaches to solving these strategic challenges) is one possible approach.

Initial MHRE Efforts

A variety of technologies and concepts must be developed to enable a 100-kWe solar-powered satellite with the capability to flight-demonstrate a variety of payload experiments and to utilize electric propulsion. State-of-the-art solar concentrators, highly efficient multi-junction solar cells, integrated thermal management on the arrays, and innovative deployable structure design and packaging make the 100-kW satellite feasible for launch on one existing launch vehicle. Higher voltage arrays and power management and distribution (PMAD) systems reduce or eliminate the need for massive power converters, and could enable direct-drive of high-voltage solar electric thrusters.

An objective of current R&D efforts, led by the NASA Marshall Space Flight Center, with the strong participation of several other organizations (including NASA centers—such as JPL and GRC—and industry—such as ENTECH and LM) is the development of a cluster of four "mini-sats" in order to address all functional and operational issues. The proposed concept consists of identical solar-powered modules, each equipped with an electric propulsion system, assembled in a reconfigurable arrangement that supports power generation redundancy and engine-out capabilities. The concept also provides for payload attachments on each module to provide flexibility and re-configurability options for accommodating multiple technology experiments and eventually different exploration payloads.

The goal of the project is to assess and mature the technologies that support future development of a modular architectures and systems; in the case of this project, a 100 kilowatt-class spacecraft suitable for on-orbit assembly and reconfiguration. The thrust of the technology maturation effort is to integrate a representative advanced solar power generation (SPG) system, high-voltage power delivery system (PDS), and advanced thermal management into system-of-systems demonstrations. The activity also will address multi-satellite rendezvous and self-assembly, as well as distributed wireless avionics and robotic reconfiguration in the event of a simulated spacecraft propulsion or power system failure.

Summary and Conclusions

Without substantial systems-level innovation and the development of tractable, but as yet un-demonstrated new technologies, a broad range of ambitious space operations beyond low Earth orbit cannot become either affordable or sustainable.

Modular, reconfigurable spacecraft, assembled in orbit from identical building-block components, is a critical capability that address the need for affordable, routine exploration, delivering cost savings through multiple-unit production, and providing options for affordable module replacement and module redundancy. On-orbit assembly will provide mission planners more flexibility in choosing launch vehicles and support hardware, increasing mission value and affordability. Figure 5 illustrates two alternate approaches that have been examined during the past decade (a monolithic square array and a monolithic 'bat-wing' array). The central question of economic feasibility is whether a modular approach can yield a substantially less expensive operational system.

As illustrated in Figure 6, there is a great potential for these high-power, advanced transportation systems to provide reasonably fast trip times for transport within the Earth-Moon system. (For example, this involves less than 4 months to transport payloads LEO to GEO, with additional time for return of the transport system to LEO for refueling and reuse.) At the heart of any decision whether or not to develop these systems is the as yet unresolved question of what 'learning curve' to use in analyzing the expected cost of such systems in operational production.

However, if the relevant technologies can be matured, and the systems developed successfully, the prospective space mission applications are remarkably broad. In the nearer term, they include Earth system transportation, as illustrated in Figure 7; while in the longer-term applications include cargo (and even perhaps crew) transportation across the illustration, as illustrated in Figure 8.

All in all, the MRHE spacecraft concept addresses many highly attractive features in a robust, scalable package. It promises at least one potential solution to an otherwise insurmountable barrier: how to achieve affordable and sustainable ambitious future space operations beyond low Earth orbit.

Glossary of Acronyms

CER	Cost Estimating Relationship
EELV	Evolved Expendable Launch Vehicle
ETO	Earth-to-Orbit (Transportation)
FTE	Full Time Equivalent
GEO	Geostationary Earth Orbit
HLLV	Heavy-Lift Launch Vehicle
ISS	International Space Station
kW	kilowatt
kWh	kilowatt-hours
LEO	Low Earth Orbit
MEO	Middle Earth Orbit
MRHE	Modular Reconfigurable High Energy (System)
NASA	National Aeronautics and Space Administration
PDS	Power Delivery System
PMAD	Power Management and Distribution
R&D	Research and Development
SEP	Solar Electric Propulsion
SPG	Solar Power Generation
TPI	Terrestrial Planet Imager
TRL	Technology Readiness Level(s)

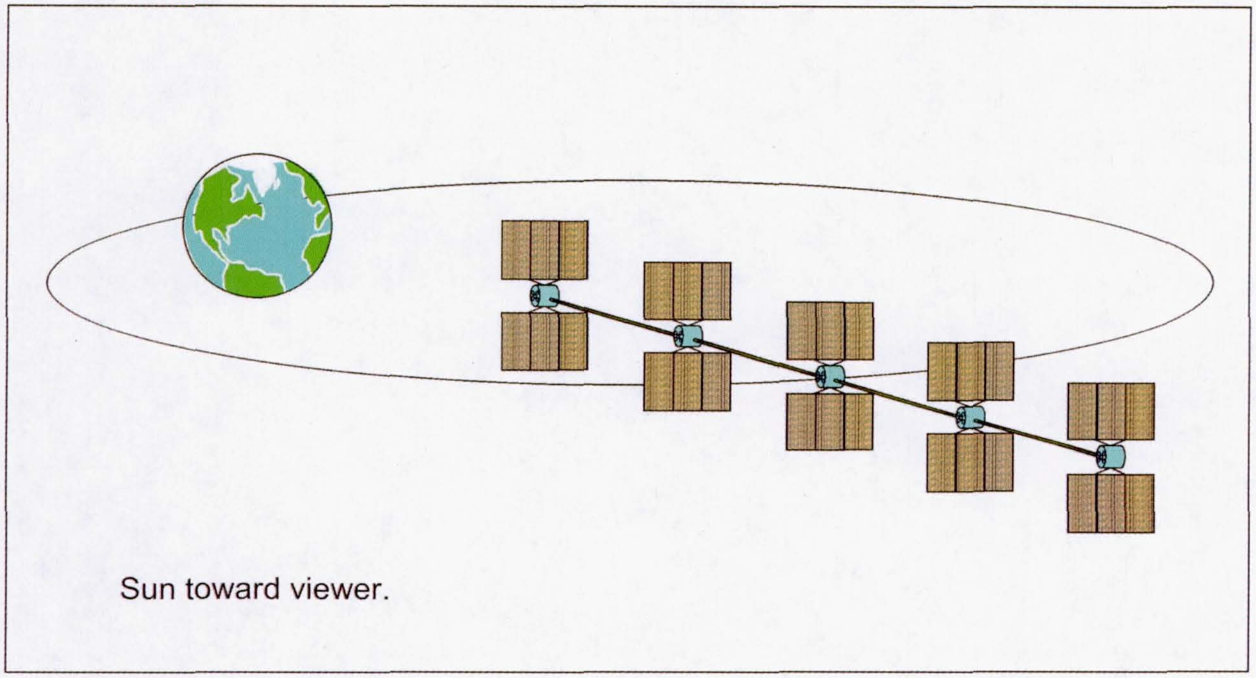

Figure 1. A Linear / Gravity Gradient Configuration Modular Reconfigurable High-Energy (MRHE) Concept

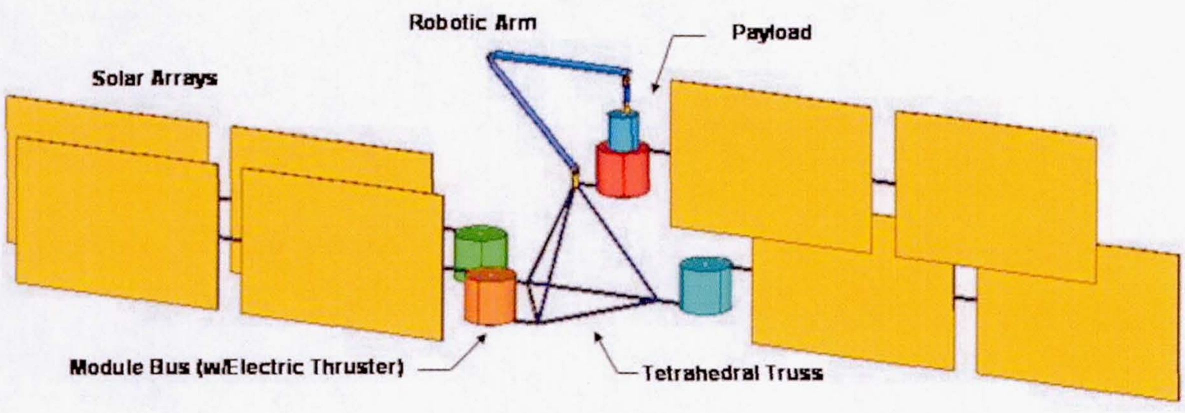

Figure 2. A Tetrahedral / 3-Axis Stabilized Configuration Modular Reconfigurable High-Energy (MRHE) Concept

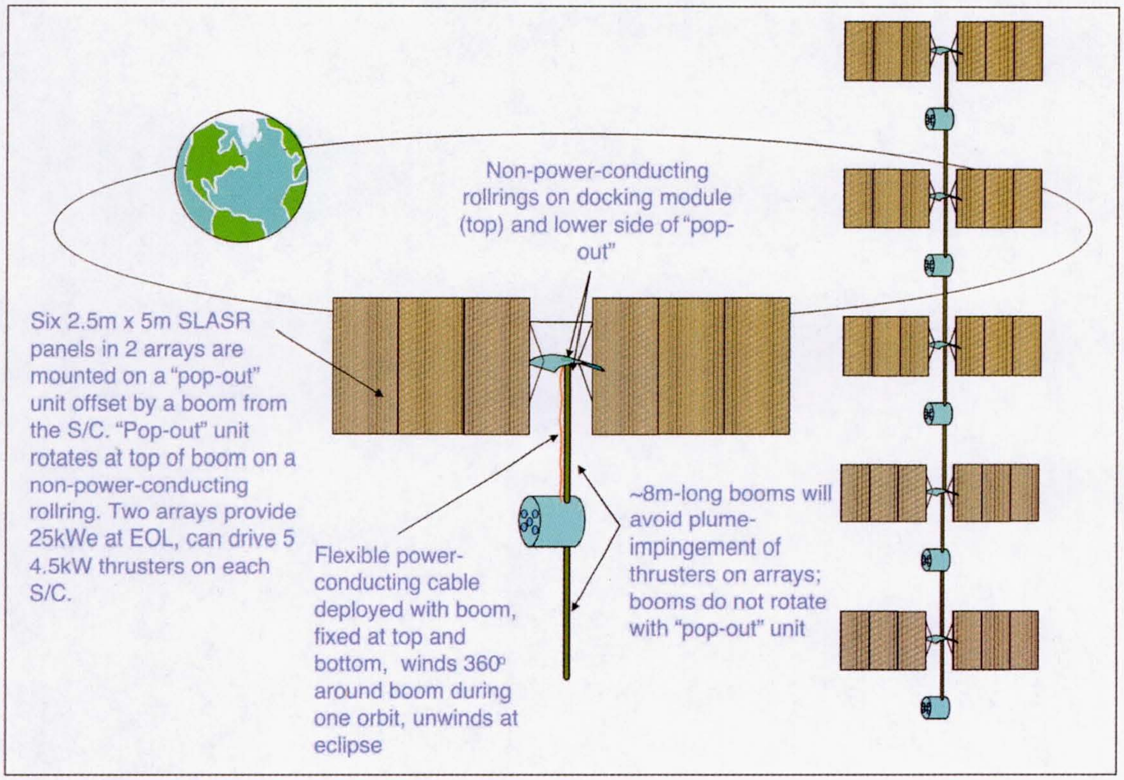

Figure 3. A Linear / Normal-to-the-Plane-of-the-Orbit Modular Reconfigurable High-Energy (MRHE) Concept

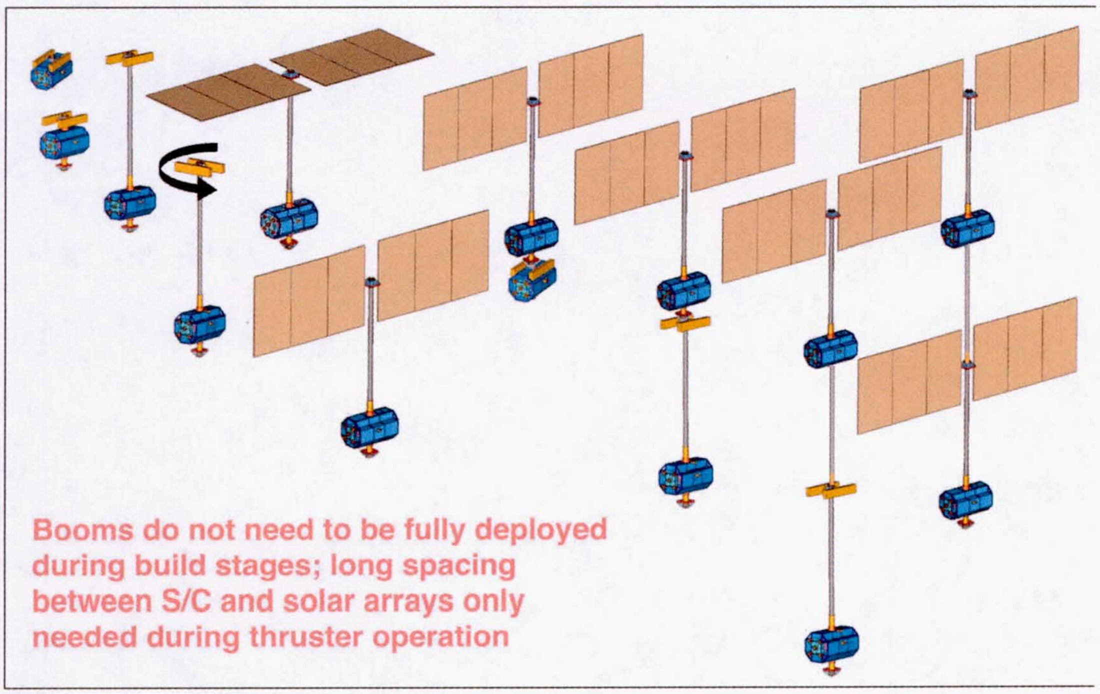

Figure 4. Notional Self-Assembly Sequence for a Modular Reconfigurable High-Energy (MRHE) System

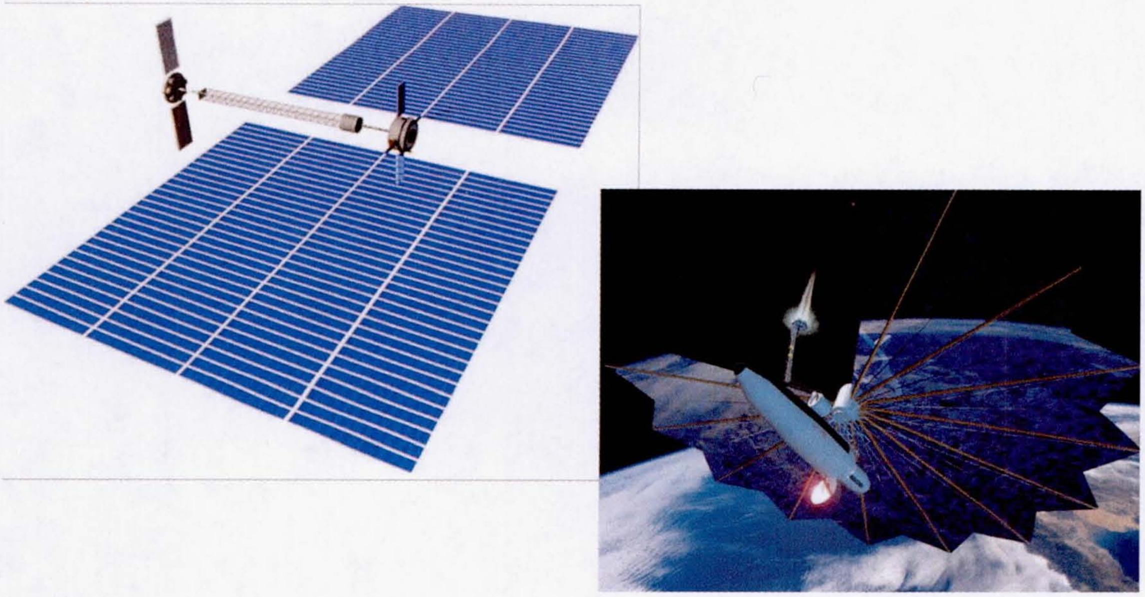

Figure 5 Alternative Large Solar Electric Propulsiojn (SEP) Vehicle Concepts (Monolithic Square Array (Left) and Thin Film "Bat-Wing" Array (Right)

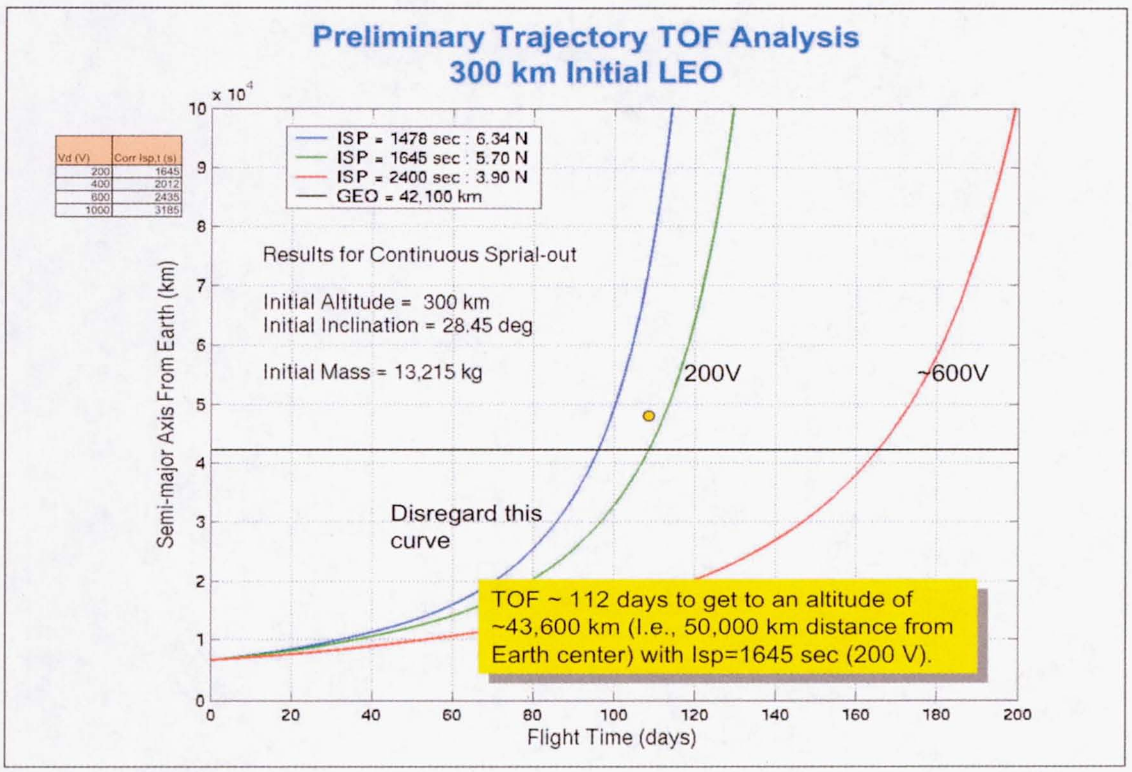

Figure 6 Preliminary Flight Times Parametric Analysis for Large SEP Systems (with varying output voltage)

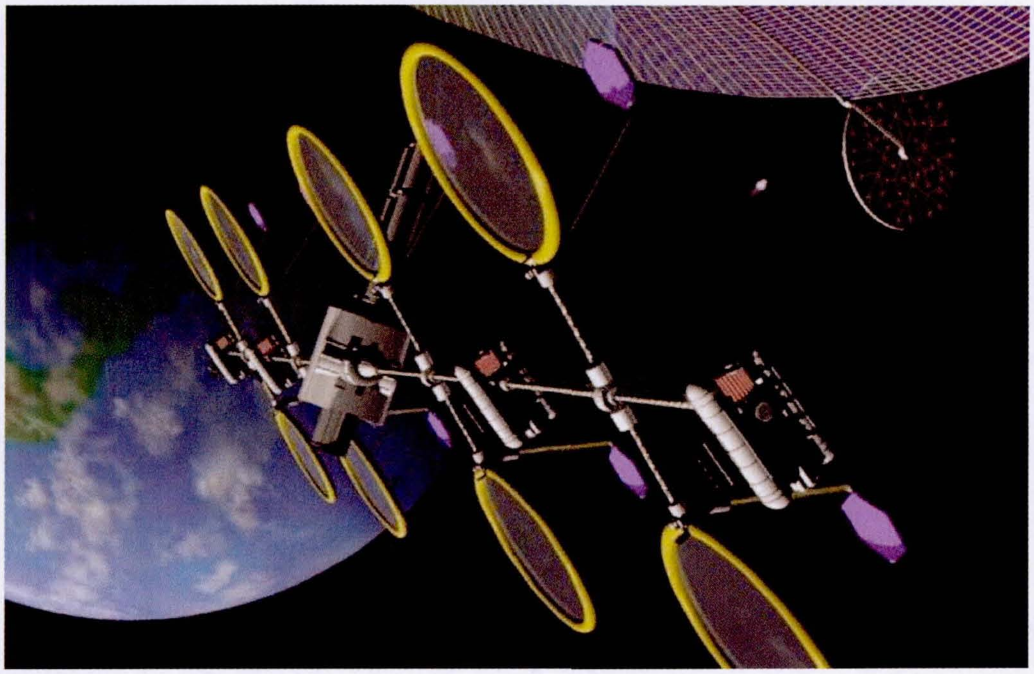

Figure 7 A notional MRHE System – an Earth-Moon System "Solar Clipper" – in operation, transporting large space systems to GEO

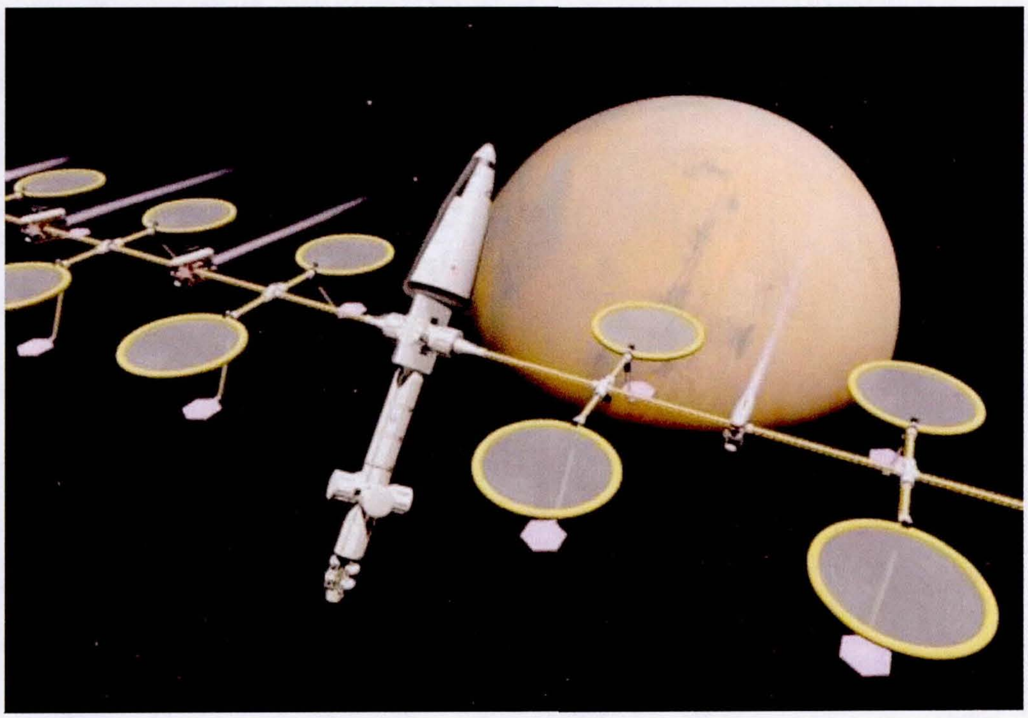

Figure 8 Another notional MRHE System – an Earth-Mars "Solar Clipper" – transporting large exploration mission systems and cargo to Mars orbit

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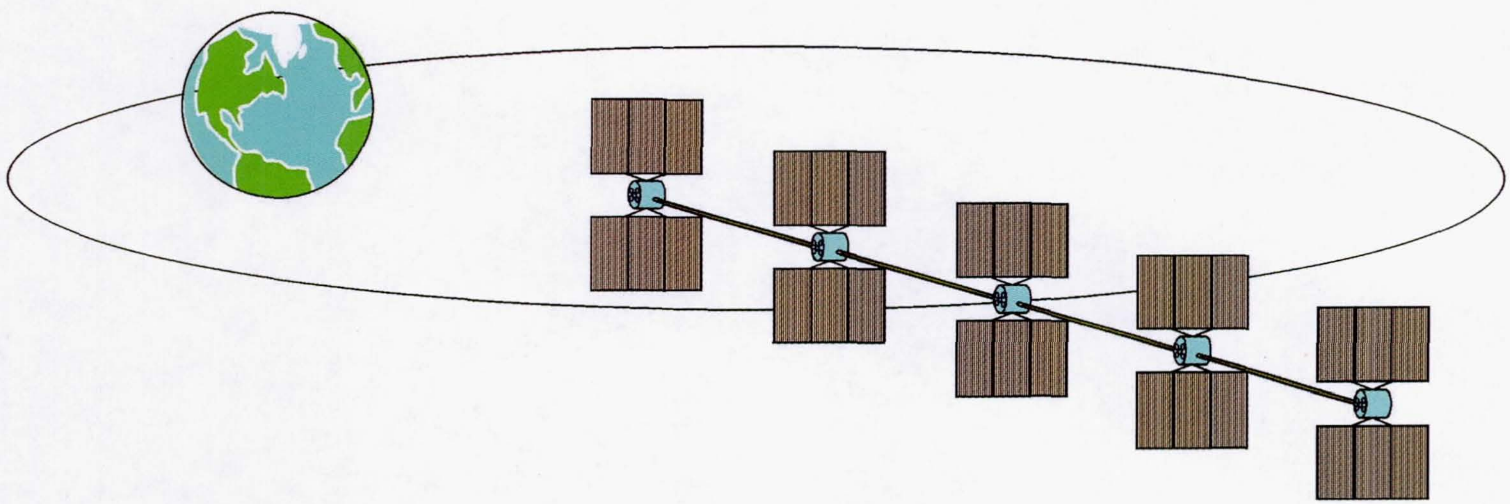
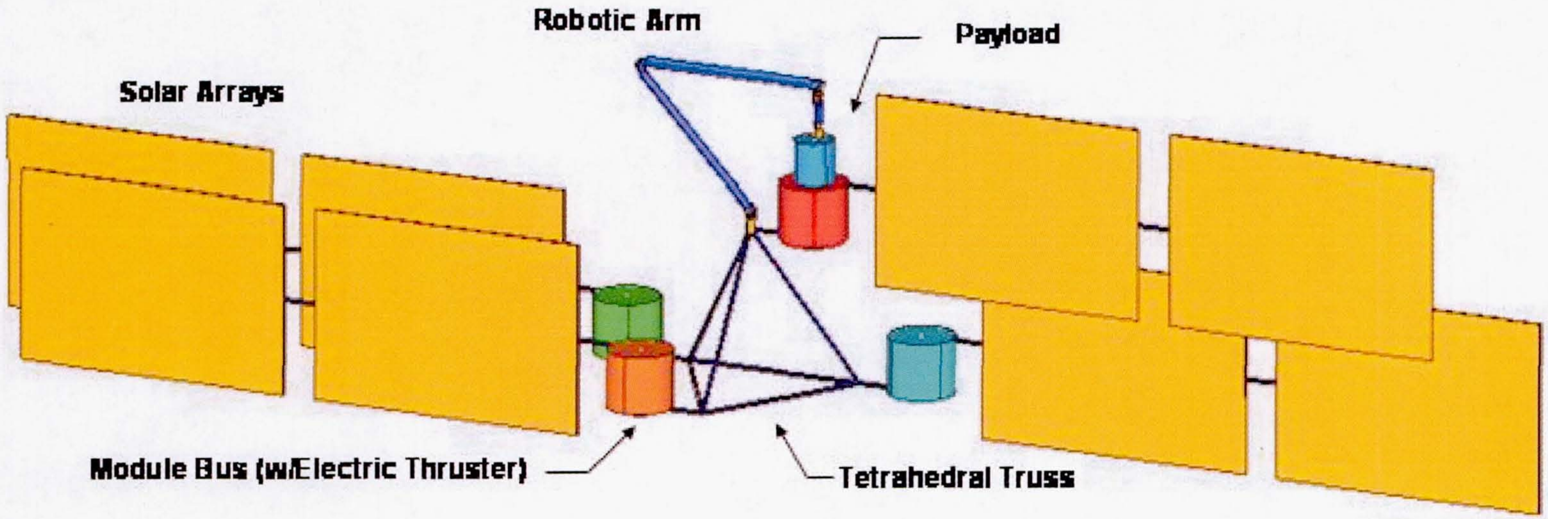
A Linear / Gravity Gradient Configuration Modular Reconfigurable High-Energy (MRHE) Concept

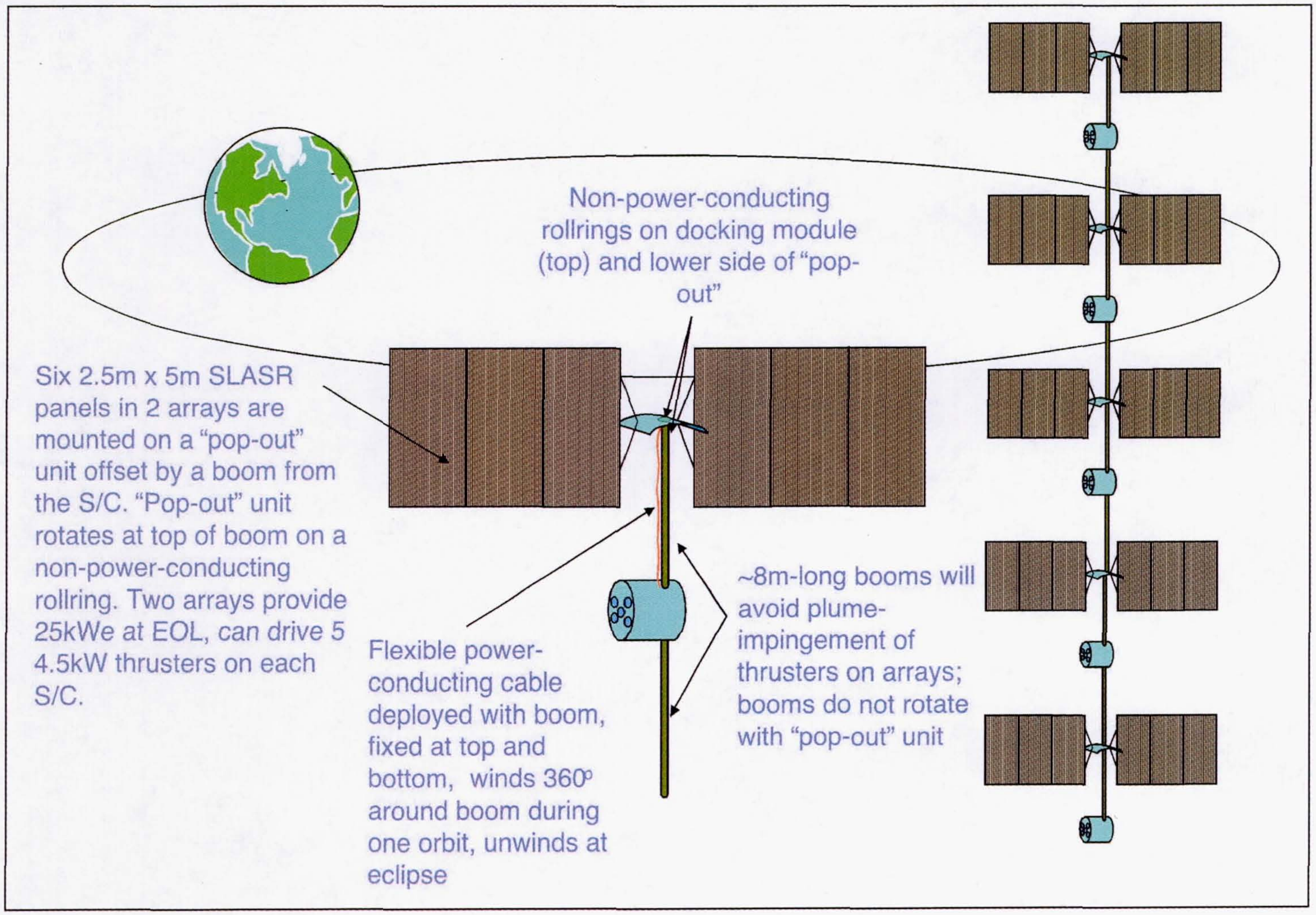


Sun toward viewer.

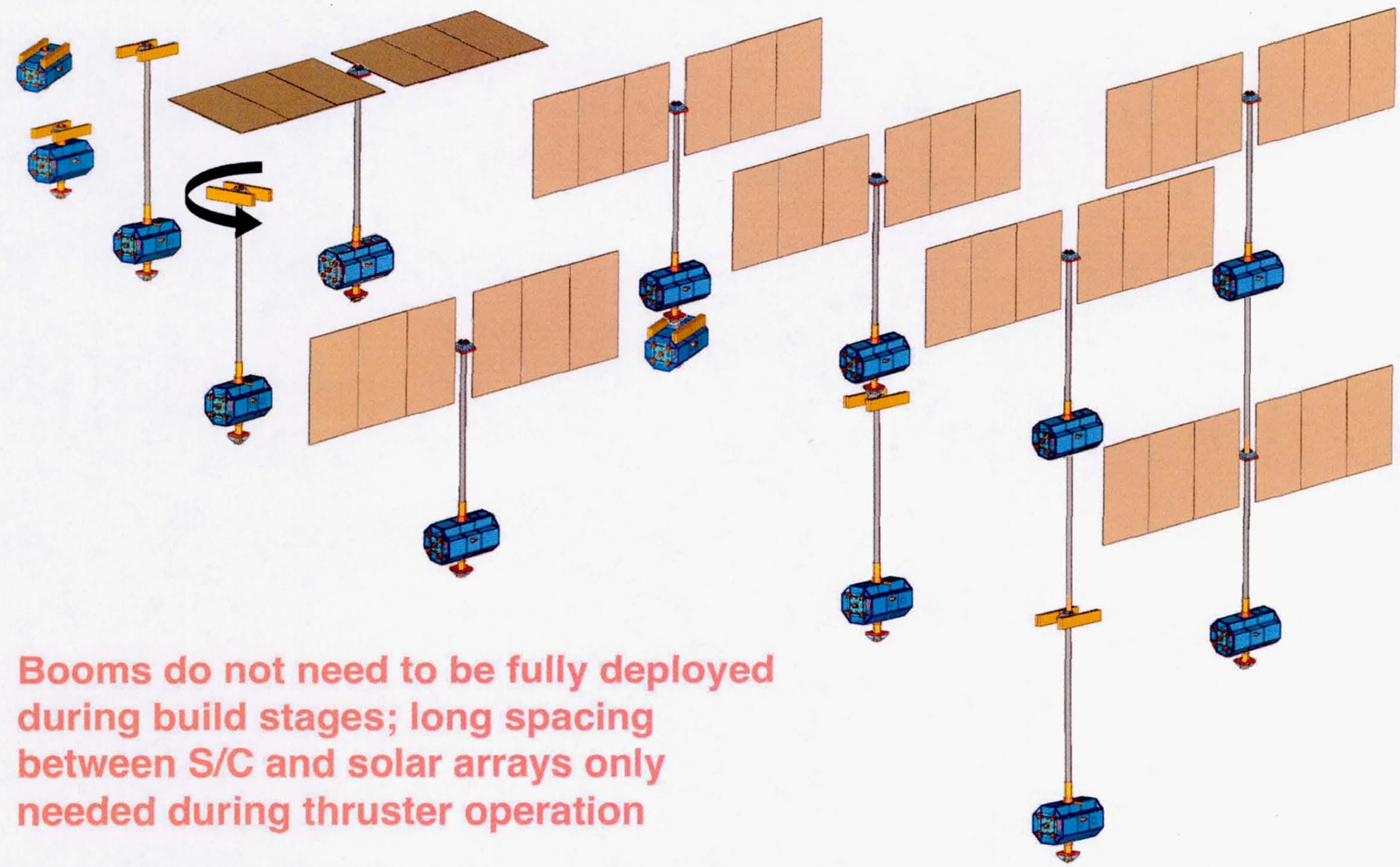
A Tetrahedral / 3-Axis Stabilized Configuration Modular Reconfigurable High-Energy (MRHE) Concept



A Linear / Normal-to-the-Plane-of-the-Orbit Modular Reconfigurable High-Energy (MRHE) Concept

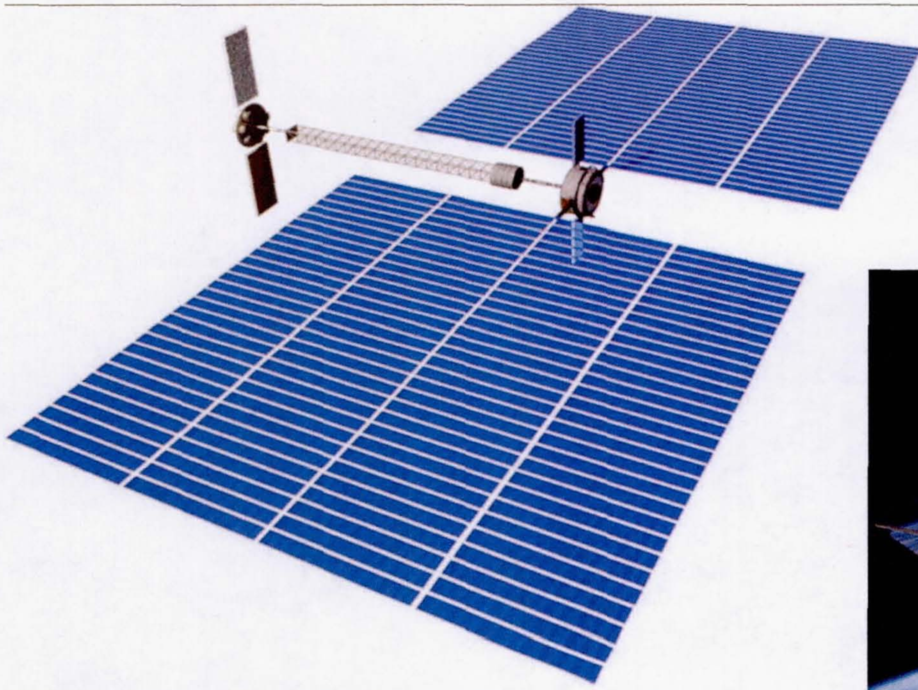


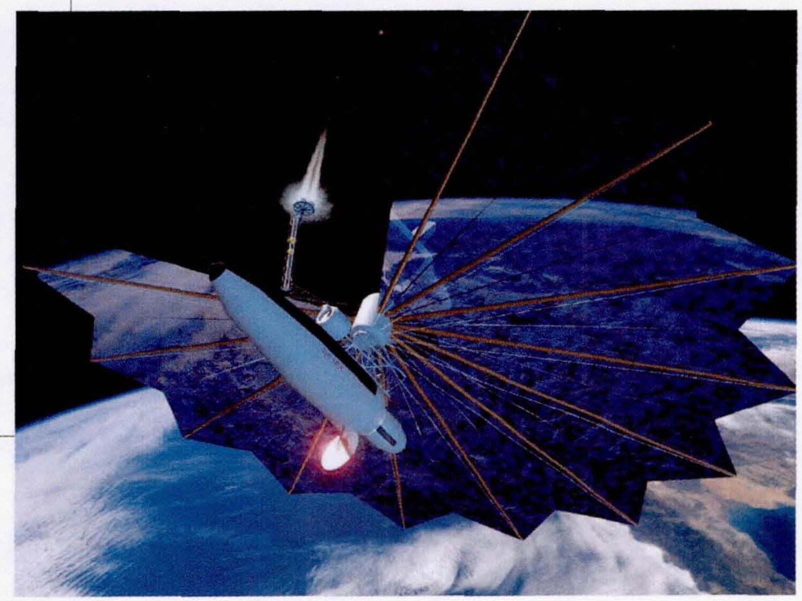
Notional Self-Assembly Sequence for a Modular Reconfigurable High-Energy (MRHE) System



Booms do not need to be fully deployed during build stages; long spacing between S/C and solar arrays only needed during thruster operation

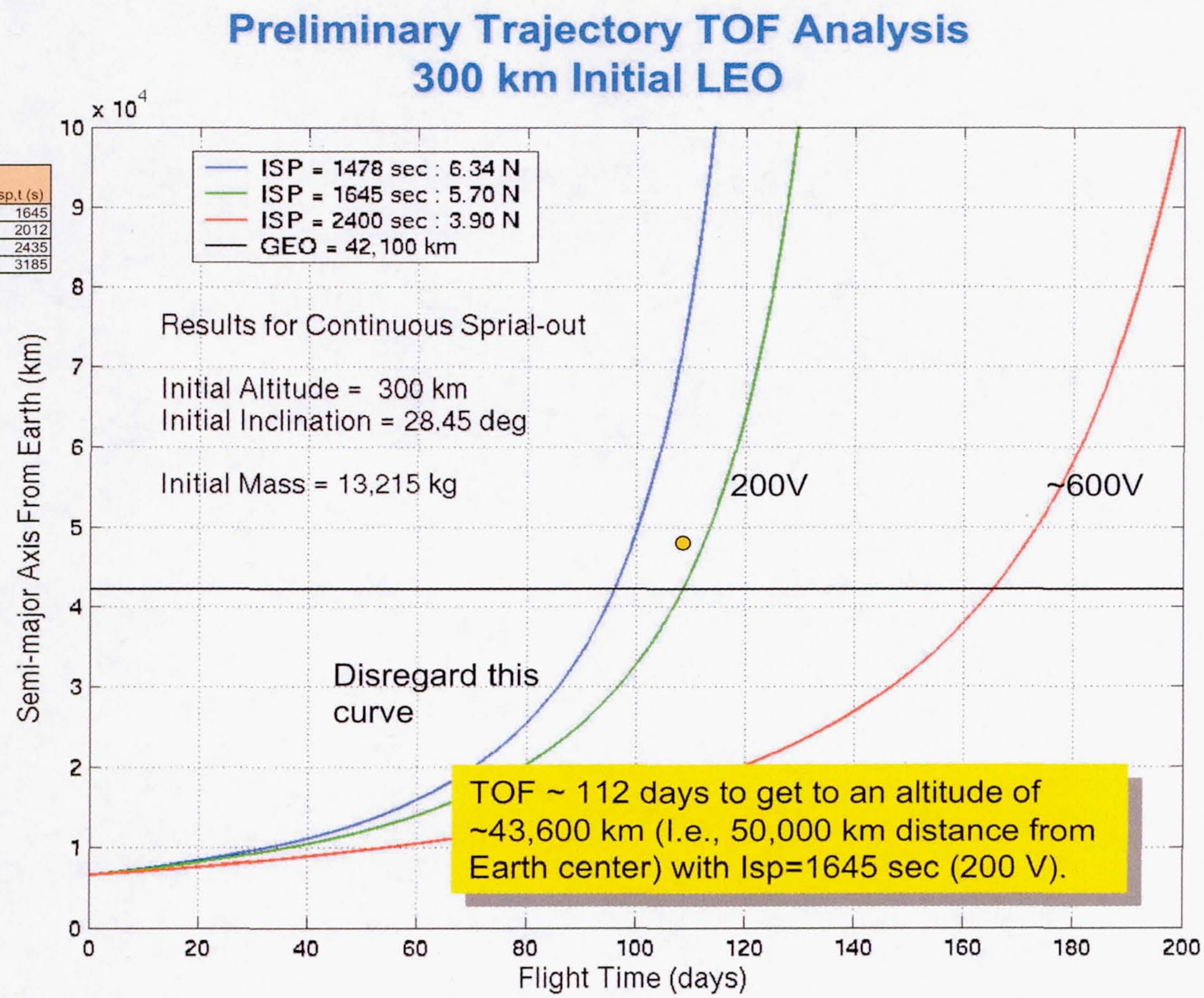
Alternative Large Solar Electric Propulsiojn (SEP) Vehicle Concepts (Monolithic Square Array (Left) and Thin Film "Bat-Wing" Array (Right)



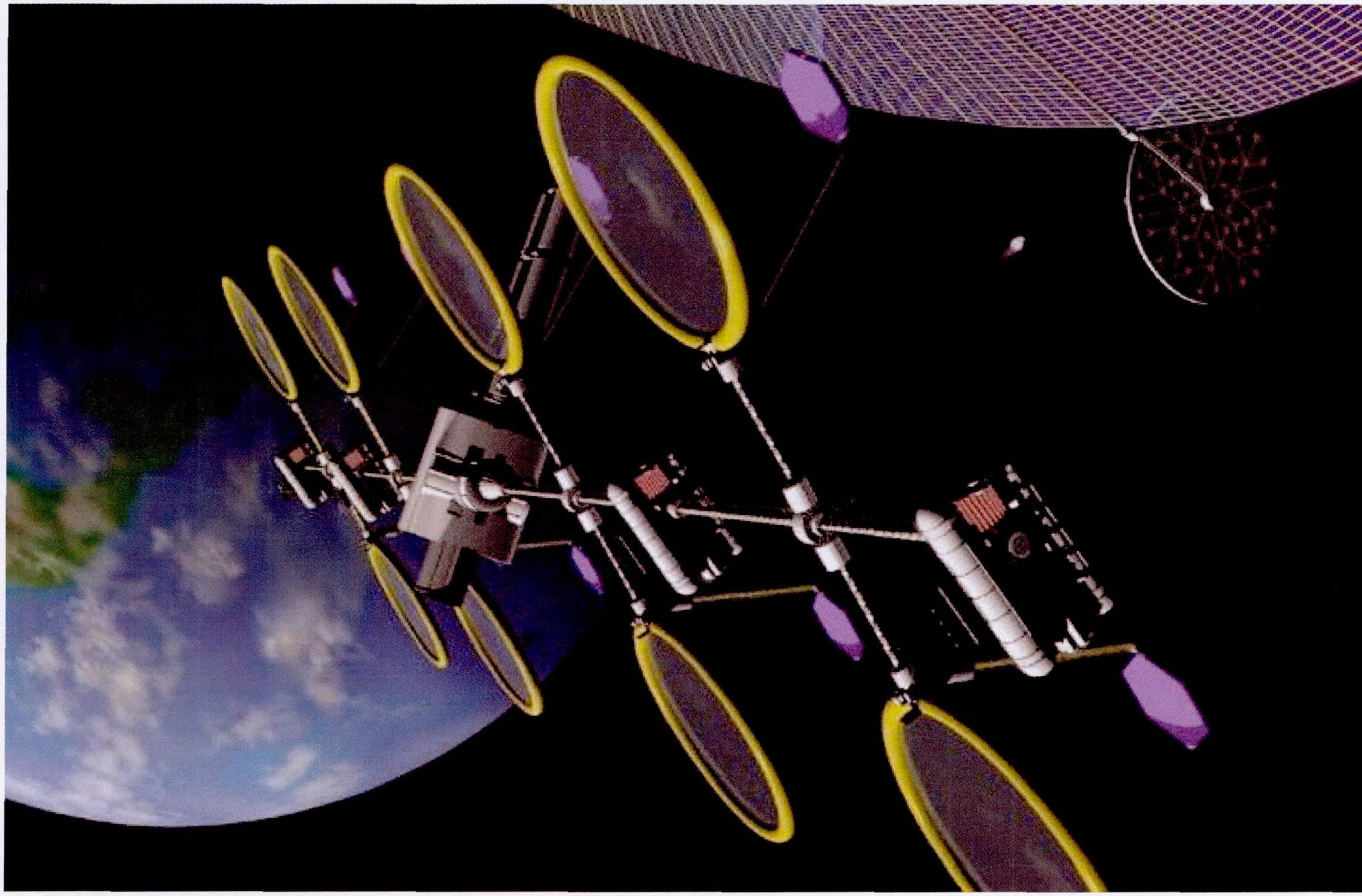


Preliminary Flight Times Parametric Analysis for Large SEP Systems (with varying output voltage)

Vd (V)	Corr Isp,t (s)
200	1645
400	2012
600	2435
1000	3185



A notional MRHE System – an Earth-Moon System "Solar Clipper" – in operation, transporting large space systems to GEO



Another notional MRHE System – an Earth-Mars "Solar Clipper" – transporting large exploration mission systems and cargo to Mars orbit