Roadmap for Long Term Sustainable Space Exploration and Service Complex - Alternate Basing Concepts

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Abstract

To achieve affordability of exploration and human habitation of space, man must learn to operate from space, e.g., space base operations to avoid the high cost of overcoming the earth's gravity well. If man is to operate or live in space, many of the ground operational functions must be provided in space. True manned habitation of space must become non-dependent on support from the earth. Previous work provided the requirements for this space operation node in space along with the requirements for a space based element required to transfer humans or cargo around in space. The focus of this paper is to assess the many options available to choose from for placement of a space operation node. Including some of the many locations that this node will support, e.g., the moon, asteroids, earth geosynchronous orbit or even Mars or Venus.

Nomenclature

i.e. = such as
ISRU = Insitu resource utilization
LCC = life cycle cost
LEO = low Earth orbit
L1 = Lagrangian Point between Earth and Sun
SPST = Space Propulsion Synergy Team
TUG = re-usable space based transfer system
VS. = verses

I. Introduction:

This roadmap is a living document being developed to establish the approach required to achieve Affordable, Sustainable Space Exploration and habitation. It is to provide a structured engineering guide for the functional definitions necessary and to allow integration at all levels arriving at the desired support infrastructure and labor needs that are in keeping with the overall affordability goals. The goals are (1) need to assure concepts are equally defined/described and complete to allow fair comparison and are responsive to the desired cost goal, (2) to assure adequate inputs are available and being made in the evaluation and analysis process and (3) provide a Structured Engineering guide that provides the functional definition necessary at all levels to allow integration at all levels. These goals are for arriving at the desired support infrastructure and labor needs that are in keeping with the overall Affordability Goal.

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Alternate basing concepts include Earth orbit, synchronous orbit, moon base platforms and etc. to enable *Affordable*, *Sustainable Space Exploration and habitation*. Initial research on previous manned habitat studies considering Lagrangian points as possible locations are also considered.

Technical paper (AIAA 2015-3892) defined the functional quality parameters required for the operational space exploration and habitation capability and the functional requirements for man to live and work in space and also defined the functional requirements of a space based transportation system needed to move material and personnel around in space.

Review of manned space habitation studies including possible Lagrangian point basing provided the source for a baseline concept selected which apply equally to Earth orbit, synchronous orbit and moon base deployment. The space operation node will include manned and unmanned operation providing many functions currently performed at ground space launch facilities, e.g.,

servicing and refueling capabilities for missions within earth orbit and beyond or refueling of existing satellites in space. If the mission is to assemble a large group of vehicles for a Mars expedition, it would not seem practical to perform this task at a "Lagrangian Point" or if the mission was to harvest resources from the moon; therefore, more trade studies to determine if one location is adequate or if several space operation node would be required.

Generic Attributes (Functional Qualities) Required for Operational Space Exploration Transportation System and the Spaced Based Transportation System are:

- AFFORDABILITY OF SPACE SYSTEM (LOW LIFE CYCLE COST)
- SAFETY OF PERSONNEL, HARDWARE, AND ENVIRONMENT
- RESPONSIVENESS OF THE SPACE TRANSPORTATION SYSTEM
- OPERABILITY OF THE SPACE TRANSPORTATION SYSTEM
- DEPENDABILITY OF THE SPACE TRANSPORTATION SYSTEM
- MAINTAINABILITY OF THE ENTIRE SPACE BASED SYSTEMS

II. FUNCTIONS TO BE PERFORMED AT THE SPACE OPERATION NODE:

A self-contained complex built and delivered to a space support location or locations is needed to support long term sustainable space exploration and habitation. Physical elements supporting in-space assembly and maintenance/servicing of long term in-space vehicles including an automated service & docking platform, fuel depot, and, other on-orbit elements required for long term servicing, fueling and payload integration. The space operation node will serve as the home for the In-space Transportation System, where it will be maintained ands serviced for many different missions in space.

This complex provides a service in-space similar to the earth located ground support system activities. These activities are designed to provide a high level of automation to the in-space support complex utilizing digital computers. The space operation node must include the devices that are required for handling, servicing, testing, maintenance, repair and fueling/re-fueling of space vehicles.

One important aspect of this paper is to assess the location for the space operation node which will provide a baseline to compare alternate locations that can meet in-space needs.

III. REQUIREMENTS DISCUSSION AND CONSIDERATIONS:

The achievement of accomplishing the goal of making space development and habitation that is affordable and sustainable will require tradeoff of the many necessary support tasks. he types of service to be performed must be defined and listed. These services might include assembly in space; propellant servicing of existing satellites in earth orbit; propellant servicing of space assembled vehicles intended for missions beyond earth orbit; space debris cleanup; man learning to live in space without earth support; harvesting and transferring material in space for delivery to the earth or use at the ground node; performing maintenance on systems in space, manufacturing replacement components to support space maintenance; and performing human medical procedures when required.

Space vehicle space operation node location and definition of a space vehicle support which is similar to current ground support system for space launch vehicles is required. The requirements for a space basing and servicing are many. They would have to provide all the material needs, in an environment out in space that is very hostile to human life.

Atmosphere

Air pressure is a basic requirement of any human supported servicing complex. Oxygen could be obtained from lunar rock and nitrogen from the Earth. Nitrogen in the form of ammonia may be obtainable from comets and the moons of outer planets. The air of a colony could be recycled in a number of ways such as photosynthetic gardens, possibly via hydroponics, or forest gardening. Most space colony designs propose large, thin-walled pressure vessel containment.

Heat rejection

The human supported servicing complex is in a vacuum and would require a means of thermal control; heat rejection, such as, a radiator to eliminate heat from absorbed sunlight. Alternate methods would distribute coolants, such as chilled water from a central radiator.

Meteoroids and dust

The space operation node would need to withstand potential impacts from space debris, meteoroids, dust, etc. Most meteoroids that strike the earth vaporize in the atmosphere. Without a thick protective atmosphere meteoroid strikes would pose a much greater risk to a service complex.

Protection from radiation

The human supported servicing complex could be effectively shielded from cosmic rays by their structure. Alternative concepts based on active shielding or less complex mass shielding and usage of magnetic and/or electric fields to deflect particles could potentially reduce mass requirements.[12]

A human supported servicing complex located at L4 or L5 would have its orbit outside of the protection of the Earth's magnetosphere for approximately two-thirds of the time (as happens with the Moon), putting residents at risk of proton exposure from the solar wind.

IV. Space Basing Major Elements

Space Tug Transfer Vehicle

Early definition of a cryogenic space tug was presented in paper AIAA 2015-3893 and a storable propellant version is being generated for comparison. Both need to be assessed from in-space support in terms of location, propellant supply and other key attributes.

Fuel Depot (One Function of the Space Operations Node)

Fuel depots have been studied since 1980"s and propellant transfer and operation demonstrated on various technologies development efforts in space. Technique and design well understood, however, which propellants and the source, resupply method and space location need final definition.

OTHER KEY ELEMENTS for early implementation (TBD)

Many of the functions intended to be performed in space will require a space transfer vehicle. To avoid the cost of escaping the earth's gravity well each time will require this space transfer vehicle to be space based. It is expected that this system will be maintained and serviced at space operation nodes. This would be supported by in-space parts manufacture and maintenance.

Location

Optimal servicing complex orbits need to be defined and orbital station keeping is probably a commercial issue. The lunar L_4 and L_5 orbits to be too far away from the moon and Earth, however, the use a two-to-one resonance orbit that alternately has a close, low-energy (cheap) approach to the moon, and then to the Earth could provide a quick, inexpensive access to both raw materials and the major market. This would not be practical or affordable for earth satellite servicing, therefore, a single complex is not likely the solution. An extensive trade study to clarify the overall need is clearly required.

For example, space operation node also known as an orbital service station designed to remain in space (most commonly as an artificial satellite in low Earth orbit) for an extended period of time and for other spacecraft to dock would be a secondary support complex..

V. ADDITIONAL ADVANTAGES OF SPACE SERVICING:

Arguments are made for space servicing having a number of advantages:

Access to solar energy

Space has an abundance of light produced from the Sun. In Earth orbit, this amounts to 1400 watts of power per square meter.[2] This energy can be used to produce electricity from solar cells or heat engine based power stations, process ores, provide light for plants to grow and to warm space colonies.

Outside gravity well

Earth will not have a gravity well to overcome to export to Earth, and a smaller gravity well to overcome import from Earth.

In-situ resource utilization

Space servicing may be supplied with resources from extraterrestrial places like Mars, asteroids, or the Moon (in-situ resource utilization [ISRU];[1] see Asteroid mining). One could produce breathing oxygen, drinking water, and rocket fuel with the help of ISRU.[1]

Asteroids and other small bodies

Most asteroids are a mixture of materials, virtually all stable elements on the periodic table can be found in the asteroids and comets and more importantly, because these bodies do not have substantial gravity wells, it is very easy to draw materials from them and haul them to a construction site.

There is estimated to be enough material in the main asteroid belt alone to build enough service complexes to equal the habitable surface area of 3,000 Earths.[4].

VI. Basing In Space Operations Node:

Possible Lagrangian point basing has led to a selecting a previous defined basing concept from manned service complex studies which apply equally to Earth orbit, synchronous orbit and moon base deployment. Review of previous studies which identified all of the above seem to direct our initial deployment to a modified Lagrange point deployment which will be discussed below.

VII. Location Considerations Using Lagrange Points

The five Lagrangian points are labeled and defined as follows:

The **L_1** point lies on the line defined by the two large masses M_1 and M_2, and between them. It is the most intuitively understood of the Lagrangian points: the one where the gravitational attraction of M_2 partially cancels M_1's gravitational attraction.

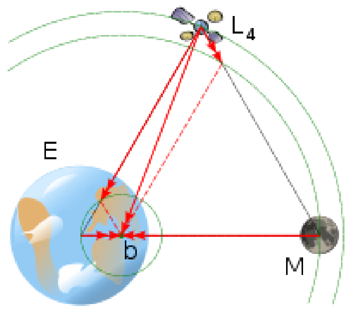
> **Explanation:** An object that orbits the Sun more closely than Earth would normally have a shorter orbital period than Earth, but that ignores the effect of Earth's own gravitational pull. If the object is directly between Earth and the Sun, then Earth's gravity counteracts some of the Sun's pull on the object, and therefore increases the orbital period of the object. The closer to Earth the object is, the greater this effect is. At the L_1 point, the orbital period of the object becomes exactly equal to Earth's orbital period. L_1 is about 1.5 million kilometers from Earth.[4]

The **L_2** point lies on the line through the two large masses, beyond the smaller of the two. Here, the gravitational forces of the two large masses balance the centrifugal effect on a body at L_2.

> **Explanation:** On the opposite side of Earth from the Sun, the orbital period of an object would normally be greater than that of Earth. The extra pull of Earth's gravity decreases the orbital period of the object, and at the L_2 point that orbital period becomes equal to Earth's. Like L1, L2 is about 1.5 million kilometers from Earth.

The **L_3** point lies on the line defined by the two large masses, beyond the larger of the two.

> **Explanation:** L_3 in the Sun–Earth system exists on the opposite side of the Sun, a little outside Earth's orbit but slightly closer to the Sun than Earth is. (This apparent contradiction is because the Sun is also affected by Earth's gravity, and so orbits around the two bodies' barycenter, which is, however, well inside the body of the Sun.) At the L_3 point, the combined pull of Earth and Sun again causes the object to orbit with the same period as Earth.



Gravitational accelerations at L_4

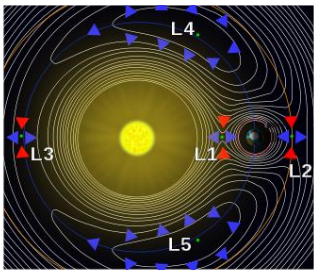
The **L_4** and **L_5** points lie at the third corners of the two equilateral triangles in the plane of orbit whose common base is the line between the centers of the two masses, such that the point lies behind (L_5) or ahead (L_4) of the smaller mass with regard to its orbit around the larger mass.

The triangular points (L_4 and L_5) are stable equilibria, provided that the ratio of M_1/M_2 is greater than 24.96.[note 1][5] This is the case for the Sun–Earth system, the Sun–Jupiter system, and, by a smaller margin, the Earth–Moon system. When a body at these points is perturbed, it moves away from the point, but the factor opposite of that which is increased or decreased by the perturbation (either gravity or angular momentum-induced speed) will also increase or decrease, bending the object's path into a stable, kidney-bean-shaped orbit around the point (as seen in the co-rotating frame of reference). In contrast to L_4 and L_5, where stable equilibrium exists, the points L_1, L_2, and L_3 are positions of unstable equilibrium. Any object orbiting at L_1, L_2, or L_3 will tend to fall out of orbit; it is therefore rare to find natural objects there, and spacecraft inhabiting these areas must employ station keeping in order to maintain their position.

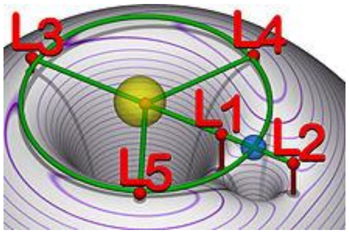
Natural objects at Lagrangian points

It is common to find objects at or orbiting the L_4 and L_5 points of natural orbital systems. These are commonly called "Trojans"; in the 20th century, asteroids discovered orbiting at the Sun–Jupiter L_4 and L_5 points were named after characters from Homer's *Iliad*. Asteroids at the L_4 point, which leads Jupiter, are referred to as the "Greek camp", whereas those at the L_5 point are referred to as the "Trojan camp".

Mathematical details



A contour plot of the effective potential due to gravity and the centrifugal force of a two-body system in a rotating frame of reference. The arrows indicate the gradients of the potential around the five Lagrange points—downhill toward them (red) or away from them (blue). Counter intuitively, the L_4 and L_5 points are the high points of the potential. At the points themselves these forces are balanced.



Visualization of the relationship between the Lagrangian points (red) of a planet (blue) orbiting a star (yellow) anticlockwise, and the effective potential in the plane containing the orbit (grey rubber-sheet model with purple contours of equal potential).[10]
Click for animation.

Lagrangian points are the constant-pattern solutions of the restricted three-body problem. For example, given two massive bodies in orbits around their common barycenter, there are five positions in space where a third body, of comparatively negligible mass, could be placed so as to maintain its position relative to the two massive bodies. As seen in a rotating reference frame that matches the angular velocity of the two co-orbiting bodies, the gravitational fields of two massive bodies combined with the minor body's centrifugal force are in balance at the Lagrangian points, allowing the smaller third body to be relatively stationary with respect to the first two.[11]

VIII. Selected Basing Location:

The lunar L_4 and L_5 orbits are now thought to be too far away from the moon and Earth. A more modern proposal is to use a two-to-one resonance orbit that alternately has a close, low-energy (cheap) approach to the moon, and then to the Earth. This is the baseline concept location and any required changes to moon based or sync orbit can be identified.

Sighting considerations

- FUNCTIONS TO BE PERFORMED AT IN-SPACE SERVICING SITE
- IN-SPACE OPERATIONS CONCEPT
- IN-SPACE OPERATIONS CONCEPT REQUIREMENTS
- IN-SPACE OPERATIONS CONCEPT FACILITIES DESCRIPTION
- IN-SPACE OPERATIONS AND CORRIDOR ACCESS

IX. Summary:

To better understand the pro's and con's of selected locations for the space operation node that address the needs for each servicing application, it is recommended that a more comprehensive study be performed to determine where the space operation nodes need to be placed in space. Servicing earth orbit applications will be very different than servicing lunar applications. Servicing needs for the planets such as Mars, Venus or Mercury or one of their moons would be quite different than earth orbit applications. The other aspect of determining these space operation nodes is what would be the order of implementation. The road map is being developed to assist in establishing an affordable sustainable space operation. It would seem that this comprehensive study to determine the space operation node and their locations is needed to then develop a long range plan for space development and habitation.

X. Recommendations

There are many options that need to be studied for determining the best selected location or locations for the space operation node. It is recommended that a very comprehensive study be performed to answer this question along with determining the priority of developments that need to be pursued.

References

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