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System Design of Large Space Structures Using Tailored Force Fields

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The ability to build massive objects in space using mass from extraterrestrial sources is key to the human exploration and development of Space. We report on progress towards space-based construction, using the concept of Tailored Force Fields (TFF). The concept and validation status are summarized for background. The paper explores options in implementing the architecture, in order to study how best to utilize the concept to advance the space program. The direct mission architecture (DMA) originally developed for concept exploration, envisaged sending a robotic Rockbreaker craft to extract raw material from a Near-Earth object, followed by the TFF construction system, all powered by solar sails. An alternative Economic Evolution Architecture (EEA) is considered, but fails due to the requirement for earth-launched mass. These scenarios are adapted into an Extraterrestrial Mass for Cislunar Economy Architecture (EMCEA) where the material extracted from an NEO is returned to the earth-moon system, where a closed microwave resonator is used to construct components of space stations, to be assembled using telepresence. The DMA is deferred until most of its challenges are addressed through experience with the EMCEA.

Nomenclature

G	= Standard Earth surface gravitational acceleration
DMA	= Direct Mission Architecture
EEA	= Economic Evolution Architecture
EMCEA	= Extraterrestrial Mass for Cislunar Economy Architecture
ET	= External Tank of the Space Shuttle Transportation System
TFF	= Tailored Force Field
Rockbreaker	= Robotic spacecraft used to produce rubble of controlled particle size from a Near-Earth Object.

I. Introduction

A critical barrier to long-term human presence in space is the inability to construct an adequate radiation shield, with a station size large enough to provide artificial gravity. Such a shield must be massive enough to guarantee adequate protection at 1 A.U. from the Sun. At present there is large uncertainty about the human resistance to the space radiation environment beyond earth orbit[1]. While partial solutions have been proposed, involving inflatable shells with water and hydrogen, plastics and strong magnetic fields or electrostatic fields[2], there are no viable alternatives to using a shell that has a large mass. Such a shell will also provide micro-meterorite strike protection far beyond what today's vehicles can hope for. This paper will first summarize a concept for building massive shapes from randomly-shaped raw material in microgravity. Then it will discuss the decisions guiding each step of the process. At the outset, we note that this problem poses some fundamental differences from concepts where mass reduction is critical, though traditional design principles of mass minimization will apply to the subsystems launched from earth. A final design for a space station, for instance, may use considerably less radiation shielding, and less than 1G artificial gravity.

This paper follows up on work done and presented over the past seven years, and leads to the question of how best to proceed towards the objective of building large structures using this concept. Due to reviewer requests, the previous work on development is discussed extensively here before proceeding to the central issue of this paper.

The prospect of tailoring potential fields for automatic, large-scale space-based construction was presented in 1999[3], and has been followed up through several papers. The fundamental phenomenon behind force-field tailoring is the force generated on objects placed within a resonator, driving them to stable locations where they organize into walls or chains. It was first shown using acoustic fields, but then extended to electromagnetic fields covering a wide range of wavelengths, particle sizes and material characteristics. While some organization of material, and even some wall formation, can be seen in experiments conducted in the 1-G environment, wall formation becomes a primary feature of particle behavior when gravity is balanced out. Starting with reduced-gravity flight tests on the NASA KC-135 Reduced Gravity Flight Laboratory using an acoustic resonator in 1997, we have shown the following through flight and ground experiments, and by reference to the work of others on different applications.

A. Reduced-Gravity Flight Test Results

1. Solid partices of arbitrary shape form **walls** near the nodal surfaces of a resonant sound field[4] when the particle size is much smaller than the wavelength (the Rayleigh regime). This is different from the well-known experiments on "acoustic levitation" which have been carried into experiments on the Space Shuttle (STS). In those experiments, the effort was to position and hold a single particle, in the ultrasonic regime where the wavelength is of the same order of magnitude as the particle diameter (Mie regime), and very high intensity is used. It is also different from the "fingers of sound" approach where again the particles are in the Mie regime or even larger, and distinct beams of ultrasound are controlled to manipulate discrete particles.

2. Materials with widely different properties and shapes, including dielectrics and metals, form walls at the same locations[5]. Thus suspicions about static electricity etc. are removed.

3. The wall formation does not depend on streaming or other phenomena unique to acoustics[6]. In fact it works better with low intensity of sound, where streaming is not an issue, provided there is only high-frequency, low-amplitude g-jitter[5].

B. Ground test results

1. The walls form at or near the nodal surfaces predicted by the solution of the Helmholtz equation for a resonator.

2. Complex wall shapes are predicted from simultaneous excitation of multiple modes, and evidence of these shapes is seen in traces on the floor of the resonator in 1-G ground experiments. However, these are too fragile to be seen clearly during the short durations of clean microgravity available in KC-135 flights.

C. Early Implications

The reduced- gravity flight experiments demonstrated the potential for non-contact shape formation in space using acoustic fields and randomly-shaped particles. However, this is limited to objects whose maximum size is on the scale of 1 meter, by the need for a closed, gas-filled container, and the longest wavelengths at which an acoustic field could be made to resonate. To build massive radiation shields in space, it was necessary to take the technology to a much wider range of wavelengths. For this, we investigated the possibility of generalized force fields, and specifically, electromagnetic fields.

D. Theory and experiments from the literature

Previous work in the literature, under various technology areas, has shown the following:

1. The forces are generated due to scattering of the waves by particles[7]. This basic idea has been known and quantified since the work of King in 1935.
2. Theory for optical tweezers and laser microscopes describes force generation mechanisms in the nanometer to micrometer size range. This is analogous to those seen in acoustics and ultrasonics, and analogous relations can be developed[8].

3. The radiation force thus generated is amplified by several orders of magnitude in a resonator, and the wall locations have high "stiffness" and stability[8]. While the acoustic resonator used in our experiments built up a field intensity 3 orders of magnitude above the excitation intensity, electromagnetic resonators in the microwave regime are predicted to offer upto 6 orders of magnitude.

The equations describing the generation of such forces in acoustics and electromagnetics are similar in form, and analogous relations were developed[9]. This has been linked back to first principles in the PhD dissertation work of the fourth author[10].

E. Scaling to Large-Scale Space-Based Construction

A rudimentary scaling for the acceleration per unit field intensity was developed from this analogy and extrapolated into the radio frequency (RF) regime[9]. Using this scaling, we predicted the design parameters for a 50m diameter, 50m long cylinder with walls 2m thick – enough to stop any radiation expected in Space at the orbit of Earth around the Sun (1 A.U.). The recent NASA reference on radiation shielding[11], gives the required shield thickness of regolith as only 0.5m, greatly simplifying the construction problem and slashing the energy requirement and the time taken to extract material and build the structure. The required solar power was estimated, to generate a long-wave radio frequency (RF) field strong enough to cause 1 micro-G acceleration on 20cm blocks of material of specific gravity 2.0 (similar to earth soil), driving them towards the stable wall locations. This acceleration level was chosen to be well above any forces exerted by gravitational jitter, solar wind or solar radiation at 1A.U. from the Sun, away from any planets or moons. NEOs of 1km diameter, for instance, would exert far less than the selected value. The wall locations themselves are stable. The point of this exercise was to check the magnitude of power input needed in a resonator to form rocks into a cylindrical wall, and relate this power to the size of a solar array required at 1 A.U. It turned out that the area of the solar array was large, but not unreasonable – on the order of 1 square kilometer at 10% efficiency. It was recognized that the 50m dimension, the 2m wall thickness, and the 10% solar cell efficiency, were all probably far from values for an optimized space station module and a construction system; however, they were chosen to be conservative limits in order to check the upper bound energy requirements. The technical challenge at this point was to validate the extrapolation of the analogy between acoustics and electromagnetics, to wavelengths and particle sizes of 20cm - far beyond the micron range of laser optics.

F. Extension to Long-Wave Electromagnetics

The electromagnetic force on a single particle measured in a microwave resonator in an experiment conducted by the Jet Propulsion Laboratory[12] is successfully and accurately predicted by the scaling relations developed from the acoustics-electromagnetics analogy[13]. Thus, experimental validation has confirmed the force expressions for a single particle of specified dielectric properties in an electromagnetic field, at the millimeter scale of particle size, in a microwave field, operating at the border between the Rayleigh regime (particle size << wavelength) and Mie scattering (particle size ~ wavelength). Our postulate is that it can also be extended to particle sizes of several centimeters, and wavelengths of 100 meters.

The above represents the state of knowledge that drove the initial conceptual design of a large station. Only walls (plates) were believed to be buildable – not rods or chains. Since low-gravity quarries for raw material implied Near Earth Objects or asteroids, and the wall formation process would be imperfect, releasing blocks of material into space would pose a prohibitive debris hazard within telepresence range of Earth. The Earth-Sun Lagrangian Point L-4 (ahead of Earth in its orbit around the sun by 60 degrees, or two months) was envisaged as a reference location with the same radiation and solar intensity immediately outside Earth's magnetic field, for the first construction station. Objects at this location are stable to small perturbations, and hence require minimal station-keeping fuel. Two subsequent (recent) realizations are summarized before exploring architectures.

Interaction forces, and Differences between Acoustic and Features of Electromagnetic Force Fields. From Wanis[10].

Acoustics / Electromagnetics
Force Profile in 2-D

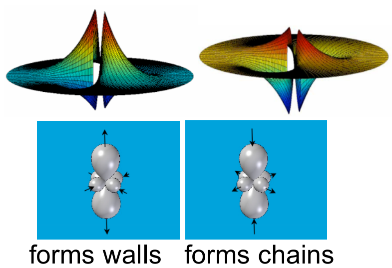
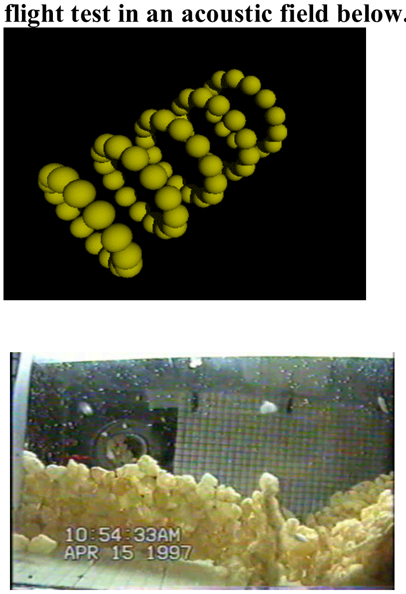


Figure 1: In acoustic fields, a particle approaching another, already at a nodal surface, experiences strong repulsion (larger lobe) along the normal to the surface, and weaker attraction along the surface, so that a wall is formed. In electromagnetics, the approaching particle experiences strong attraction along the line joining the particles, and weaker repulsion along the other coordinates

Figure 2: Electromagnetic fields form chains rather than the walls shown forming in a reduced gravity flight test in an acoustic field below.



While the radiation force that drives particles towards preferred surfaces in the resonant field is analogous between acoustic and electromagnetic fields, and the scaling for power is valid, the wall formation process is quite different. This difference merits a separate discussion below. Wanis[10] has developed, through physical and numerical experiments, a consistent model for self-organization of particles in resonant standing wave fields. The implication of his work is that in acoustic fields, particles will self-organize along surfaces, and form walls one particle thick, but further control within the surface is difficult. In an acoustic standing wave field, particles drift towards nodal surfaces. In electromagnetic fields, however, self-organization can be taken to one level finer in control. Particles can be aligned and joined together along specified lines, forming chains or rigid links of desired shape. This is illustrated in Fig. 1. Once the chain is fused together, it can be treated as a single particle, and other chains or particles can now be attached to it, depending on its orientation.

The implications are that:

- By turning the field direction, these elements can then be combined to form more and more complex structures.
- By changing wavelength, the construction process can thus go from fine-scale structures, assembled at higher and higher levels into larger structures.
- Alternatively, electromagnetic construction thus offers the potential to form various other shapes, including long struts and curved structural members. Figure 2 shows a structure forming from chains in an electromagnetic field, compared to walls forming in an acoustic resonator in microgravity flight test.

With the above background, we proceed to discuss architectures for implementing the concept on a large scale. It is recognized that the architecture and system design relate to a concept that is still a few years from reaching a technology readiness level suitable for flight; that there are several steps of validation required in the concept itself, and some of the technologies applied are some years from reaching the level assumed. However, this is why it is appropriate to use System Engineering descriptions at this stage to explore the best route to implementation in missions. The following discussion is generally based on the standard processes described by Pisacayne[14]

G. Revisiting the O'Neill Cylinder Problem: A Side Note

The problem of building Space Stations has been discussed since the 19th century, and was intensely analyzed both by the Soviet Union and by the US. The NASA/ASEE Study of 1977 examined the issues in detail following the work of Gerard O'Neill, and several of the directions chosen here were derived from those studies. In previous work[15], we re-examined the NASA/ASEE study, and detailed the construction of a 2km diameter, 2km long spinning cylinder as a large-scale habitat in the Earth-Moon system. This would be constructed using a cylindrical wire grid of lunar-manufactured steel cable, with rings of 2m-deep railcar-sized steel containers full of regolith being welded together by a construction robot – the regolith would provide the soil base for agriculture or other resource extraction as well. The containers would be launched by a set of ten lunar equatorial mass-driver launchers, each powered by a lunar power plant. The entire process could be automated, and achieved using telepresence supervision from Earth over a ten-year period. However, it would only make sense in the context of a coherent plan for a massive Space economy, with a well-developed lunar component. This type of construction is not considered further in this paper.

II. Requirements For Massive Structures In Orbit

A. The Context For Building Massive Structures In Orbit

Large space stations will not be built for science alone – the budget and incentives must come from beyond just a national space program. There are 3 reasons to build a massive structure in orbit rather than on a planetary surface:

- It is a habitat for humans who must commute to workplaces in orbit, e.g., power satellites, manufacturing facilities or for maintenance functions.
- It is a long-duration mission, such as a mission to Mars. Further, it is likely to be a routine mission, such as a Cycler[16] that stays in orbit, or perhaps a military earth-observation station that requires human presence.
- It is a tourist hotel with some staff stationed for long durations.

Any of these presupposes planning towards a space economy, with one or more of the following present:

- Space-based large-scale manufacturing or solar power plants.
- Regular missions to Mars or other planets (again presupposes an economy there)
- Routine launches from earth inexpensive enough to support a flourishing tourist business.

This does not presuppose that low-cost services exist already – *just that such interests are involved in the planning*.

In this paper, we consider much smaller space stations than the 2Km cylinder mentioned above, intended as outposts for the first human explorers on long-duration missions in the solar system, presumably for resource development. This is conceived as occurring in a near-term space economy development plan, tied where possible into the present NASA plans for exploration of the Moon and Mars. General choices are listed in Table 1.

Table 1: Morphological Matrix

Location of Construction/ Methods	Earth-Sun L4/L5	Earth Orbit	Earth-Moon L2/L5	Mars/Asteroids
Human Intervention	Robotic / delayed telepresence	Human presence	Telepresence	
Construction	TFF	Building Blocks	Space Debris Refit	Inflatables
Source of Material	Terrestrial	Lunar	NEO	
Construction Type	All at Once	Assemble Parts Made in Space	Assemble Earth-launched parts	Assemble lunar-launched parts
Radiation Protection	Physical Blocking	Electromagnetic Shielding	Water-filled walls	Hydrogen-filled walls
Adhesion Method	Sintering	Mechanical	Welding	Tensile elements
Power System	Photovoltaic	Nuclear	Fuel Cell	Solar direct conversion
Propulsion System	Chemical Rocket	Nuclear Rocket	Electric Propulsion	Solar Sails
			Total Possibilities	147,476

B. Broad Objectives & Constraints

The objective of the program is to solve the problem of building habitats in orbit, massive enough to provide radiation shielding and 1-G. The fixed criteria are given in Table 2. The requirement for complete radiation shielding is not excessive, since the craft/ structure should be designed for orbits that include segments of closer approach to the Sun. The requirement for 1G artificial gravity is somewhat arbitrary, since humans may adapt quite well to lower levels. However, there is insufficient data on the level needed for long-term human adaptation, and a 1G specification would permit lower levels at different parts of the station, while ensuring that the station is designed to the strength needed for 1G. Note that the G specification is the primary criterion for structural strength.

Shield construction: Decider for extraterrestrial materials.

Radiation shielding must protect against high-speed massive particles (cosmic rays) as well as high-energy gamma rays and X-rays, and charged particles from the Sun, without generating lethal secondary emission that occurs when high-energy particles encounter metal skins. Per the rule of thumb cited above, a 0.5m is thickness of earth or lunar regolith (composed mostly of silicon dioxide) is adequate as a passive barrier to all types of radiation. It is easy to see that the radiation shield mass for a long-duration habitat must come mostly from extraterrestrial, low-gravity sources, if reusable machines can extract the mass.

Table 2. List of Requirements.		
#1	Launch Date	Deployment aimed at 2025
#2	Capacity of structure	Nominally intended to hold at least 50 people for long-term habitation, plus supplies, laboratories, greenhouse, micro-g access, and some resource extraction facilities
#3	Radiation Shielding	Complete radiation shielding in all working and living enclosures, so that level inside is no more than that indoors on Earth, when the structure is at 1 A.U. from the Sun.
#4	Artificial Gravity	1G at its living quarters (other parts of the structure may be at low or zero-G)
#5	Rotation Rate	Below 1 RPM threshold of disorientation, to accommodate 97% of population.

C. Quantitative Estimate of Mission Needs and Requirements

Table3: Mission Needs and Requirements		
Need	**Rationale**	**Driving Requirement**
Compatibility with NASA ESAS for earth-launch	Use of CaLV, CEV and limited lunar resources/ development	#1
Volume needed	50m dia x 50m long cylinder modules (5)	#2
Mass for 5 modules	6,000 tons (0.5-foot thick at 2000kg/m$^{3)}$	#3
Strength	1G steady load due to rotation	#4
Mass of Support Structure	20 tons, primarily tensile elements.	**#4**
Station Radius	1000 m	#5

Why 50m cylinders? There is little precedent for choosing the size of a standard station module for long-duration human habitation in space. Since existing concepts for Mars Cyclers and Astronaut Hotels assume that all components are launched from Earth, they are necessarily derived from the dimensions of rocket parts, which in turn are limited by frontal area in order to reduce aerodynamic drag during ascent through the atmosphere. A long-duration, sheltered facility is likely to serve many functions including housing, laboratory space, vehicle docking and repair, medical / quarantine facilities, airlocks for extravehicular activity, food storage, preparation and even agriculture, common spaces, and playgrounds. Metaphors for such a self-contained, long-voyage station might include cruise ships, aircraft-carriers, or crude oil tankers, but with substantially more space per person. The 50m cylinder, 50 m high, was chosen to be compatible with a 100m wavelength in the initial concept analysis, and considered to pose an upper limit to the challenges that might be demanded of a new construction technique.

D. Links to the Present

The architecture specification[1] for the present Moon-Mars Initiative defines NASA plans for launcher systems and extraterrestrial operations. Specifically, the Cargo Launch Vehicle is rated at 125,000 kg payload to LEO, with an estimated launch cost to LEO[17] of $8000/kg at the production rate envisaged for the present NASA plans. Table 4 lists several issues relevant to lunar operations and materials scenarios, along with an estimate of their present Technology Readiness Level[14], and some rough guess of their probability of fruition. Table 5 lists several technologies being developed on Earth, and projects their level in the timeframe required for the habitat construction project. Based on Tables 3 and 4, lunar resources are not used in the DMS baseline, since there is no reasonable probability of a high-capacity launcher operating routinely from the lunar surface before 2025. NEOs appear to be a better prospect at least as a low-gravity source of large mass for use in sending regolith into orbit.

Table 4: Lunar operations and materials scenarios				
		TRL (est)	Year deploy	Readiness Probability
Power	SNAP-10A,500w, ZrH, U-235 Reactor, orbited 1957[18] Lunar-made solar cells[19]	8 6	2015 2020	0.5 0.3
Oxygen	ISRU	5	2020	0.5
Regolith	ISRU	5	2020	0.5
Metals	ISRU	5	2025	0.3
Other gases	ISRU	4	2025	0.2
Telepresence Operations	Earth-satellite – surface probe[20]	9	2015	0.9
Robotic Operations	Earth-satellite – surface probe[21], [22]	9	2020	0.9
Lunar commercial-scale launcher	Mass-driver	5	2025	0.5
NEO identification	Telescopes; flyby	10	2015	0.9
NEO rendezvous	Hayabusa followup	9	2020	0.9
NEO resources	Flyby; probes	4	2025	0.5

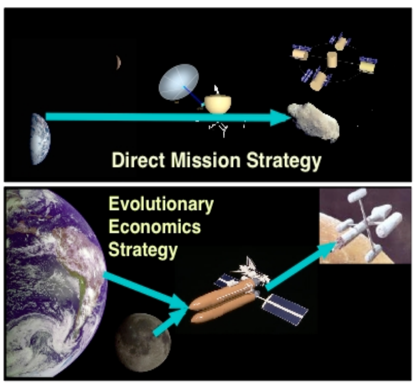
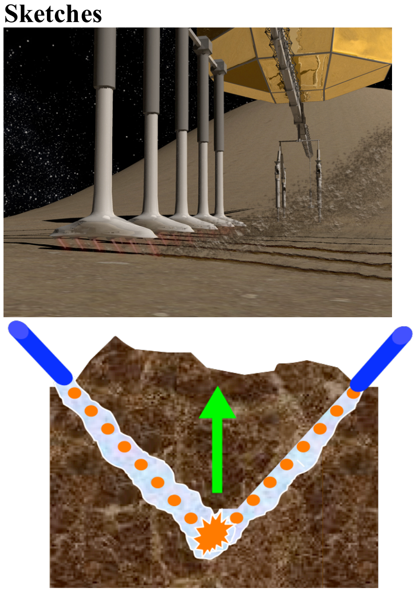


Figure 3: DMA vs. EEA: In DMA, the material is extracted and formed near a low-g object. In EEA, material from earth or other sources is formed into the structural skeleton, and filled with the shielding material.

Figure 4: Rockbreaker: Conceptual Sketches



E. Alternative Mission Concepts & Architectures

As seen above, work on Electromagnetic Shaping indicates that continuous chains of particles can be formed, providing control at a lower level (one more degree of freedom) than is possible using acoustics, where only walls can be formed. This makes intuitive sense, since electromagnetics involves vector fields as opposed to scalars. This raises a fundamental choice between two strategies:

The Direct Mission Strategy (DMS) is to build versatile construction machines and send them to low-gravity quarries of extraterrestrial material, to build a large radiation-shielded habitat. Presumably, such quarries will be Near Earth Objects, which can be reached with modest velocity increments.

The Evolutionary Economy Strategy (EES) is to manufacture small elements, integrates them with new markets in a Space economy, and then assembles parts into large structures. Presumably, in the latter case the mass will come from the Moon, and the construction will occur in the Earth-Moon system. This paper starts evaluating the choices.

III. Direct Mission Architecture: Construction System Evolution

In the DMA (see Figure 3), the strategy is to send up a re-usable set of construction machines that can extract NEO material and build the external radiation shielded shells of several habitats with a standard module design. The size of the module is selected to pose a limiting case, rather than an optimized one. The construction is assumed to occur at a location such as earth-Sun L-4, which is at the same distance from the Sun as Earth, and is out of telepresence reach from Earth. For conceptual design, a suitable NEO is assumed to exist at the construction location. In a later iteration, this design was tested on a construction mission to a specific NEO.

The architecture depends on two robotic systems. The first is a multipurpose craft called the "Rockbreaker" (Figure 4). This craft is to rendezvous with a suitable NEO, selected for its negligible spin, and rocky material.

After attaching itself to the NEO, the device is to use its cutting arms to generate the proper size particles (construction blocks) for the TFF generators. Vanmali et al[23] described an Integrated Rendezvous Anchoring Maneuvering System (IRAMS) to attach the Rockbreaker to a microgravity NEO. This system is a combination of 4 pulsed solid-grained plasma thrusters that double as manevering units and impact torque screwdrivers. At the final moment of touchdown, the thruster reverses, and the reaction to its impulse is transmitted through the solid grain into a torque to drive a deep-thread augur into the surface. Once attached to the surface, the two telescoping cutting arms deploy, and the 60 hybrid plasmajet-sheathed laser cutters dig trenches in spiral patterns on the ground around the lander. Each cutter is a truncated linear aerospike nozzle, where the plasma jet forms the outer sheath, and the laser beam comes out of the truncated base. The cutting laser beam is protected in a plasmajet sheath which serves to clear away the melt from the laser beam, and provide the pressure inside the trench that lifts blocks of required size out of the trench, and sends them floating into space at the desired velocity, overcoming the weak gravity field of the NEO. Thus the cutting action of the two arms generates a helical cloud of blocks of the NEO material, floating slowly away from the NEO.

A. TFF System Operation Overview

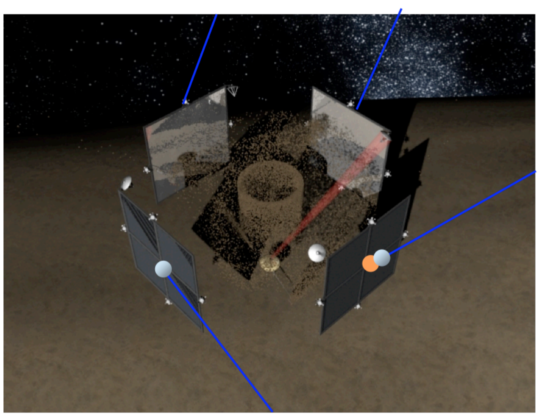


Figure 5: The four sides of the TFF resonator, shown moving away after forming a cylinder. The Rockbreaker is shown far below on the NEO surface, with power beamed to it. The long rods extend to the solar sail/collectors which are not shown.

The arrangement to form a cylinder from the rubble floated up by the Rockbreaker, is shown in Figure 5. The TFF system consists of four robotic spacecraft, which arrange themselves into a Fabry-Perot resonator. The intense radio-frequency field inside the resonator forms the rubble into a cylindrical shape. Higher-frequency beams from arms attached to the resonator (or to the Rockbreaker if possible) are used to sinter the rubble in place, providing enough strength to hold the cylinder together in zero-gravity when the field is turned off. Subsequent layers of rubble are formed concentrically on the first cylinder using slightly different modes of excitation, and sintered in place.

1. Formation and Sintering Operation

The sintering operation commences as one of the side walls of the resonator moves away allowing a second Rockbreaker craft to access the side and beam energy onto the particles, with the resonator spinning slowly about its axis relative to the particles held in the cylindrical wall inside.

Depending on the desired thickness and construction of the habitat walls, multiple walls may have to be formed. There are different options for this. One option is to form another layer of rocks around the first, using a slightly different mode. Another is to form several interspersed rings. In the EM field, switching to another mode can induce attraction between the wall and new incoming particles, forming thicker walls. These would have to be sintered in place. The sintering is a laborious process requiring considerable robotic intelligence, maneuvering of the sintering arm, and perhaps the whole craft, and hence will consume propellant, but the pace required is slow. Vanmali et al[23] calculated that this process would take roughly 19 hours (not 19 days as written in that paper) to form and sinter 10 layers of 20cm thickness each. The limiter on rate is the cutting rate. During this time, the resonator would have to move at near-constant speed relative to the NEO to stay with the spiral cloud of blocks being sent up. With the 0.5m shell thickness now sought, the time would come down by a factor of 4 or more.

2. *Finishing assembly*

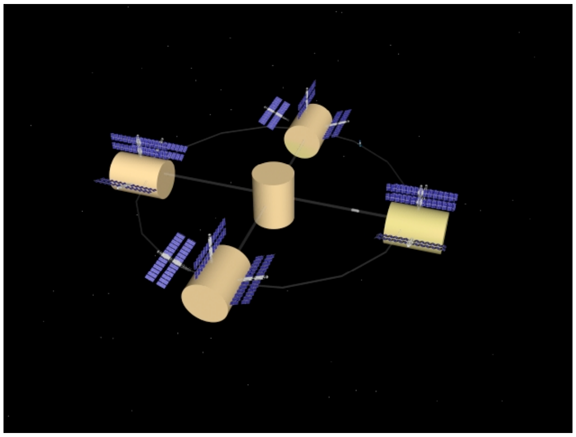


Fig. 6: 1-G Station comprised of five 50m radiation-shielded cylinders

The rest of the construction of the station and the assembly of the five modules, can be accomplished using smaller robotic craft, with the help of the RockBreakers. Figure 6 shows a completed 5-module station.

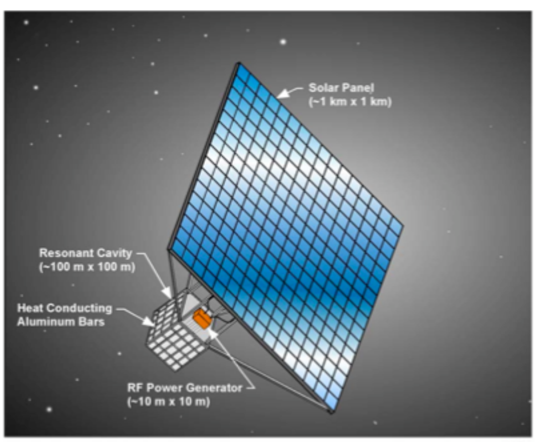
3. *Refueling the Rockbreakers*

The maneuvering propellant and cutting gas of the Rockbreakers can be common, and hence a refueling operation can be done with a single rendezvous with a tanker sent from Earth. Refurbishment of the lasers and the NEO-rendezvous IRAMS thrusters poses a tougher challenge, but again may be accomplished by ejecting old thrusters, one leg at a time, and picking replacement thrusters from the tanker.

B. Initial Design of the TFF craft

These craft are essentially pieces of an electromagnetic Fabry-Perot Resonator. They incorporate conducting grids spaced at a small fraction of the wavelength range where they are expected to operate. Their surface shape can be modified using extensible members driven by electric motors, also used in their deployment in space. Two such craft would form the resonator ends, while the others would form an enclosure during the buildup of the field until the particles are already at stable locations. Following that, one wall can move away and accommodate a sintering arm from a Rockbreaker.

Figure 7: Artist's conception of the TFF system, with a 1km x 1km solar array



Artist's rendering of space craft system assembled in orbit.

Each of the four sides of the resonator is sent to the construction location from Earth as an independent spacecraft which we will call a "TFF craft". Each incorporates a large (100m x 100m) thin-film microwave reflector, with a loop antenna in the middle. The power conversion equipment to generate microwaves of the required power, account for most of the mass of the craft. In the implementation developed by PSICorp[24], the conversion proceeds from solar cell to DC current, and thence through a set of vacuum devices to microwave frequencies ("Vacuum tubes" is not appropriate because the environment is a more perfect vacuum than any created on earth). The power comes from solar energy. In the initial realization of this craft, a 1 square-kilometer array of 10% efficient solar cells was considered as the power source. Recently, PSICorp[24] has refined this to a projection of between 28 and 42 percent efficiency by Year 2050, giving an array area of 0.93 to 0.68 sq. km respectively. Taking the lower limit of efficiency, we get an array mass of 472 tons, so that each craft has to carry a 118-ton array. The substrates of the solar arrays pose a huge mass penalty, which puts the system mass too high. Figure 7 shows a PSI design, where the entire power comes from a single panel, and the resonator is an integral box. In later designs, we chose to use four essentially identical pieces, as shown in Figure 5.

C. High-intensity Solar Cells and Concentrator

In a second iteration, the solar array was replaced with a much smaller array of high-intensity solar cells. A concentrator made of ultra-light material was conceived as the way to capture a square km of solar power and focus it onto the high-intensity array. Arrays with peak temperatures over 3000K have been demonstrated in the laboratory, which also minimize the need for other heat radiators.

The high-intensity array was seen as a placeholder concept, to be used until an effective direct conversion system for solar power to microwave was developed. Such a device now appears possible, given the recent demonstration[25] of a high-efficiency converter from direct sunlight to visible laser wavelengths, with a claimed efficiency of 38%. Since it is not yet possible to estimate the mass of such a device at the scale required for the TFF craft, the high-intensity array is used as an upper-bound mass estimate. Assuming a10-fold intensification the array mass per craft comes down to 11,800 kg. The rest of the craft has a mass of only 4600 kg, giving a total mass of the TFF components of 16,400 kg. This leaves 13,600 kg of subsystems for propulsion, control, communications and other items, to bring the craft mass within a 30,000kg target at escape from Earth orbit.

In these implementations of the architecture, the Rockbreaker craft would not carry their own primary power arrays for the rock-cutting operation. Instead, they would depend on beamed power from the TFF craft. This of course posed tough tracking challenges.

D. Integrated Solar Sail Primary Propulsion and Power Collection: Design Sizing

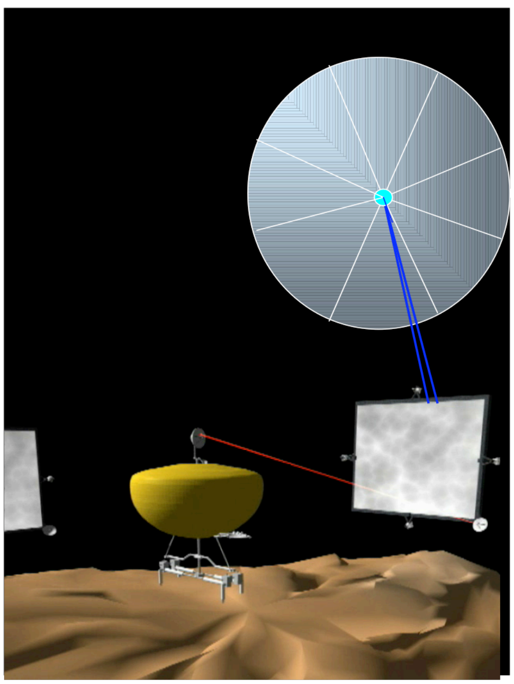


Figure 8: Artist's conception of a TFF craft beaming power to a Rockbreaker about to rendezwous with a NEO. Art by Waqar Zaidi

Given the need for a solar concentrator, solar sail propulsion is attractive. It was realized that the size of the sail required for the power focusing application is of the same order of magnitude as that needed for propulsion. ***Thus the design was driven by the sail size needed for propulsion, within the near solar system***, understanding that this provided a large reserve of power for the TFF and Rockbreaker operations. The use of solar sails greatly reduced mission mass, since there is no need to carry ion engines and propellant, except for maneuvering.

A sample NEO rendezvous study shows that the transit time to NEO 1996-FG3 is on the order of 2 years, using a solar sail mission[26]. Rangedera et al[27] extrapolated the results of this study to design a mission concept to send a solar-sailed craft in the 38,000 kg class to this NEO. 1996-FG3 has an orbit that reaches close to the orbit of Venus at perigee, and about 2/3 of the way to Mars from Earth at Apogee. The sail size required is .51 km^2 using nested solar sails. This large size allows the sail to serve as a power system as well as the primary thrust system in the cruise leg of the transfer. The transfer to the 1996FG3 orbit is a spiral orbit characteristic of low thrust missions. The Rockbreaker mass breakdown is given in Rangedera et al and showed that the sail system could be developed well within the above propulsion system mass allotment, for both the TFF craft and the Rockbreaker. A single TFF craft with its solar collector/sail is shown schematically in Fig. 8, beaming power to a Rockbreaker.

E. Direct Solar Laser: Pathway to the Evolutionary Architecture

The Direct Solar Conversion Laser mentioned above (Ref. 24), enables a breakthrough. ***This laser is very similar in basic operation to the Nd Fiber Lasers envisioned as the primary cutting devices in the Rockbreaker***. The lasing wavelength is also the same, so it may be confidently integrated into the cutter systems. Now the power conversion system from solar-electric DC to the AC needed for the laser, may be replaced with the direct-conversion laser, with some marginal power converted for the plasmajet etc. Part of the stagnation temperature needed for the plasmajet could come directly from the waste heat of the direct laser conversion. ***With the direct conversion laser, the RockBreaker becomes independent of the TFF craft***. The solar sail would have to be carried with the Rockbreaker, and perhaps tethered to the NEO in case of rotation. This decoupling of the TFF craft and the Rockbreaker is a very important realization, as we proceed to the Evolutionary Architecture.

F. Remaining Obstacles to the DMA

Table 5 lists some of the technologies needed for the Direct Mission Architecture, and Table 6 lists the steps. The DMS architecture is definitely long-term, and poses substantial engineering challenges.

- The requirement to build the entire shell structure in one continuous operation, poses daunting robotics challenges of maneuvering, visual quality control, precise positioning and control of sintering probes and an intricate tracking to position the TFF resonator around the Rockbreaker's output spiral cloud of rubble, while also tracking the sun with one or more solar collectors.
- The Rockbreaker craft will require resupply of plasma thruster gas and replacement of solid plasma thrusters.
- The interior and the attachments of the station modules will have to be accomplished by robotic missions following the construction machines. This architecture is similar in philosophy to building an entire system of habitats, at a very low per-unit cost. The overall requirement of Earth-launch missions is summarized in Table 6.
- Finally, it is not clear if a suitable non-rotating NEO of appropriate composition can be found, with an orbit that can be reached with reasonable delta-v and mission time.
- Once the massive shell is built, further propulsion will be needed to bring it to a useful orbit.
- While none of these is a show-stopper, this architecture only becomes viable when there is a need to produce a series of large modules.

Table 5: Technology development

	Demonstrated	**20 yr projection**
Solar Sail	Aereal density[28]: COSMOS-1 600sqm/100kg	Target[29] 0.1g/m^2
Ion Propulsion	~ 1N; T/W ~0.001	Improvement in thrust.
Nuclear Propulsion	RTDs	Thermal
Robotic Operations	Remote power plants on earth; Mars; Titan	Lunar, Martian, NEO robots
Beamed Microwave	Efficiency 0.5; 140GHz	200GHz; efficiency 0.8
Laser Cutter	10KW, 30% efficient Nd-fiber industrial use[30].	100KW
Cutting Nozzles for vacuum	Aerospike nozzles demonstrated on X-33. Plasmajet cutting used in industry.	Mature commercial technology
Direct solar conversion	38% efficient direct solar-conversion to Nd-Cr fiber laser demonstrated[25]	39% direct solar conversion efficiency**Error! Bookmark not defined.**
Plasma Beam	Industrial use	mature
Food growth	STS experiments	ISS and lunar base expts.
RF resonators	Military systems for RF weapons	High intensity RF common.
Vacuum devices	Large RF systems. PSICorp designs[24]	Used with solar power satellites.
Solar sails	Aereal density[31]: COSMOS-1 600sqm/100kg	Target[32] 0.1g/m^2
Ultralight booms	ISS experience, solar sail work	
In-space robotic refueling	Re-boost packages being developed; DARPA studies in-space refueling	Spacecraft routinely refueled.
Robotic sintering	Powder sintering studies for low-mass heat shields. Robotic drilling and welding in auto industry; NASA Mars drilling experiment	Feasible

Table 6: Steps in the Direct Mission Architecture

Step	**Years from decision**
CaLV launch #1 sends 2 Model scale TFF craft with sample rocks to high earth orbit for system proof experiment	10
CaLV launch #2 carries 2 full-scale RockBreaker Craft to LEO / earth escape Each sends two 38,000kg craft to earth escape velocity Each craft uses Reconfigurable Solar Collector as sail to NEO Rendezvous using plasma thrusters	12
First two craft reach NEO and prove rendezvous and operations.	14
CaLV Launch #3: 1st set of 2 resonators, each 38,000 kg payload, to NEO by RCS	12
CaLV Launch #4: 2nd set of 2 resonators, each 38,000 kg payload, to NEO by RCS	12
CaLV Launch #5: 3rd set of 2 resonators, each 38,000 kg payload, to NEO by RCS. Two	15

CaLV launches held in reserve. Estimated launch cost: $20B + $8B reserve.	

Table 7: Comparison of DMA with current space projects

Task / Requirement	**Comparison to current projects/ technologies**
Total of 500,000 kg to LEO in ~ 10 to 20 cargo launches including mission testing. Final Construction System ~ 200,000 kg at Earth escape	ISS ~ 187,000 kg to-date
Robotics	ISS robotic arm; Mars rovers.
NEO rendezvous	Hayabusa mission
NEO Cutting	NEAP mission
Final Station assembly	ISS-scale station robotic assembly; TransHab inflatable module deployment

IV. Economic Evolution Architecture (EEA)

The Economic Evolution Architecture adopts a strategy of waiting for the development of infrastructure in Space, through a progression from today's large projects. TFF would seek a variety of small applications, and thus solve the technical problems gradually. Thus there is little risk involved, and no technology is developed specifically for long-term human habitats.

a. TFF technology would be first put to use through several science missions, covering a wide range of applications. The technology of these applications will be developed through flight experiments, including those on the ISS or an equivalent orbital facility. Thus, this stage requires partial occupancy of approximately 5 human-carrying / resupply launches to the ISS.

b. The next step would be to set up an orbital manufacturing station, where lunar materials and earth-launched materials/ instrumentation would be combined into structural elements and machine parts with unique properties. Such a station would take as much in earth launch as the Mir station for construction, even if human presence is minimal on them.

c. The orbital manufacturing station would most probably be constructed from rocket parts such as expended fuel tanks and upper stages. This is a mechanical rendezvous and robotic construction operation, that can be performed by telepresence from Earth. It poses no serious technological challenge. However, this is likely to take the equivalent of two CaLV launches.

d. Following this, various useful parts and machines would be assembled in orbit for delivery to the lunar surface or other spacecraft, gradually expanding the capabilities. Clearly this presupposes a routine, low-cost orbital transfer tug in the Earth-Moon system, presumably a commercial operation with competition and redundancies. It also assumes that there is a market for manufactured products on the Lunar surface. Manufacturing facilities in orbit make sense because the delta-v required to get there is less than that needed to get to the Moon, and so is that for delivery to Earth markets. Launching raw materials from the Moon is not nearly as expensive, given efficient lunar launcher systems such as mass drivers. The establishment of this capability is likely to be combined with the establishment of other such orbital facilities, however, its marginal requirement for launches is estimated at 2 CaLVs.

e. The first in-space stations made primarily of lunar materials will be constructed, with high-strength skeletal structure and inflatable shells strengthened with spray-dried materials, then filled with regolith, hydrogen or water for radiation protection. This operation will be high-profile, and require as much earth-launched mass as ISS, since it is the radiation-shielding that is primarily being provided from elsewhere.

The outstanding disadvantage of the EEA is that there is no movement towards enabling delivery of large mass from beyond earth. Dependence on earth-launched mass negates any possibility of reaching the ability to build large orbiting habitats. While there may be excellent business plans for TFF along this route, none of them will lead to the primary objective of TFF, which is to form massive structures.

V. Baseline Extraterrestrial Mass For Cislunar Economy Architecture (EMCEA)

A. Summary of Options Considered

Going back to the context for building massive structures, we see that the development of a space economy, and an urgent national / global imperative to exploit space resources, would be the primary driver for both approaches. In the first case, a large construction plan would have to be developed, to precede human occupation. This certainly appears far-fetched today. In the case of the EEA, the obvious critical point is how to get enough mass of raw material to make manufacturing facilities viable, so that there will be enough markets. The launch cost from earth is prohibitive, and lunar launch of large mass at low cost appears to be far in the future.

B. New Realizations

- Electromagnetic shaping can form more intricate objects, such as chains of particles. Thus it becomes worthwhile to consider piecemeal construction of smaller components and assemble them.
- With newer estimates of shield thickness, the amount of mass needed is reduced by a factor of 4.
- The Rockbreaker can be decoupled from the TFF craft, so that it can extract mass from a suitable NEO, without requiring that construction should occur there.
- With smaller parts, the Electromagnetic TFF is suitable for construction inside confined spaces. The Space Shuttle External Main Tank offers adequate volume to construct a confined electromagnetic resonator in the radio frequency regime.
- If mass is brought from elsewhere, and is controlled while being fed into a confined resonator, then there is no objection to using TFF in the near-earth region.

C. Overview of the Architecture

The baseline architecture adapts features from both the DMA and the EEA, and solves some of the worst objections to each. It appears efficient to learn how to build various elements, not just massive shells. If framework for large structures can be built cheaply in orbit using tailored force fields, those elements can be assembled by robots into more efficient structures. It is also unlikely that radiation shielding for space stations or vehicles will use the full 0.5m-thick regolith approach. Instead, instrumentation and storage cabinets, water and hydrogen storage in walls, and polymer sheets, will all be combined along with perhaps a thinner layer of NEO material, to form the radiation shielding. The baseline architecture will thus call for the following:

- Integrate manufacturing facilities and experimental facilities using the ISS / other station and rocket-part assemblies. The most commonly-advocated approach to getting a large enclosed volume in orbit is to use Space Shuttle External Tanks (ET) boosted to stable orbits, and attached to form facilities that can be used for manufacturing using telepresence. It appears that boosting these to GEO or Earth-Moon L-4 may be appropriate for long-term use, once their interiors are completed. Human occupation is not contemplated, since these will not have adequate radiation shielding. Telepresence is adequate for operation from Earth.
- Use reusable Orbit Transfer vehicles (OTV) to take construction machines modeled after the RockBreaker from LEO to near earth-escape (high-apogee orbits) where solar sail deployment or a reaction engine firing can send the machine on its way while dropping the OTV back to LEO. This would save an estimated 7500 kg from each of the 6 machines described as being launched from Earth in the DMA.
- Capture building blocks and other resources extracted from an NEO quarry in a low-mass bag, and send them back to earth orbit using solar sails. This mass would then be captured for use in manufacturing facilities located, say, at the Earth-Moon L4 or L5.
- The captured material, once brought to Earth orbit, can be processed through several steps to extract resources, and some of it will no doubt find use for agriculture, etc.

- This would set up versatile construction operations in the Earth-Moon system, and feed a cislunar economy.

This combined architecture has strong advantages in that robotic construction can be replaced by telepresence assembly. The mass from the NEOs can be brought to the Earth-Moon system where they can be processed to extract other valuable resources before using the remaining soil for construction purposes. The need to send 120,000 kg (of resonators) to the NEO and conduct complex robotic operations there is avoided, replaced by sending collector bags with maneuvering thrusters, using the solar sail conveyance system. The problem of propelling the bags back to Earth orbit is easier than that of propelling a completed radiation shield back to Earth orbit as one unit.

D. Electromagnetic TFF facility in Earth orbit

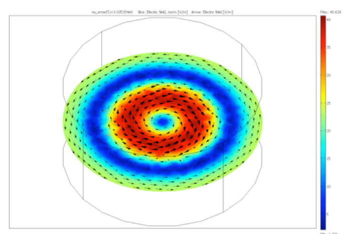


Figure 9 Electric field inside cylindrical resonator operated in the "doughnut" Transverse Electromagnetic Mode. Color denotes gradients in electric field. Arrows are directed along electric field gradient. Chains are expected to form along the direction of electric field, denoted by the above arrows.

What will such a facility be? In exterior appearance, it is no different from the concepts published for stations built using ETs. In the TFF case, the stations will not have spin, and will strive for clean micro-gravity. It will have provisions for docking the craft, bringing large mass resources from NEOs and extracting the raw material. The interior of the TFF facility is simply a microwave resonator, and it is possible that different shapes of product will require different resonator configurations. The problem reduces to the creation of different transverse electromagnetic modes, such as in a laser cavity, a phenomenon familiar to all who have struggled to avoid them while aligning laser systems. A good physical discussion of this[33], for the Helium-Neon laser, shows that combinations of modes can be obtained by rotating a piece of glass inside a laser cavity, which corresponds to changing the boundary conditions to alter the small-signal gain at different modes. For instance, a field such as that shown in Fig. 9 (finite element simulation) can be produced in an axisymmetric resonator with perfect magnetic conductors as the side walls, while the end walls will be perfect reflectors. This would be conducive to building circular rings and assembling them into tubes. To remove formed objects, the side wall will include a cargo door. Power will still come from large solar collectors. Other resonator shapes are being investigated for the structural elements that they can generate. A very large container is not optimal here, since the acceleration per unit intensity that can be achieved is generally higher if the wavelength chosen is lower.

E. Other Pacing Items

Critical pacing items for these approaches are:

- Development of national policy to build a space economy that extracts resources from extraterrestrial objects. This must be accompanied by some changes in Space Law regarding property rights. A discussion of the issues, and some possible solutions, is given by Komerath[34].
- Development of the technology for efficient direct conversion of sunlight into laser or other beamed energy.
- Solar sail / reconfigurable collector technology.
- Development of the TFF technology.

F. What Advantages does TFF offer in the EMCE?

Given our finding that the first steps to constructing massive objects should be done via telepresence in the Earth-Moon system with mass imported from NEOs, is there any benefit to using TFF rather than more conventional means of building objects? The advantages are in non-contact formation and fabrication, in facilities that can serve as tooling for a wide variety of shapes, materials and objects. The frequency, boundary conditions, and perhaps some aspects of the geometry will have to be altered, but with these, the facility can be versatile, and become attractive relative to launching specific machinery and molds for specific items. Given that the container is closed, acoustic, rather than electromagnetic, shaping could again be used for part of the size range, and the facility can benefit from the commonalities between the acoustic and electromagnetic versions of the technology. Once the technology is developed, and space-based electromagnetic fabrication becomes more routine, we would step up again to the DMA strategy, where massive habitats would be formed quickly at far-away locations. Hence the EMCEA offers both a viable medium-term economic rationale, which incorporates the advantages of the EEA, and a long-term transition to large-scale construction and rapid expansion of the human presence in Space with the DMA.

VI. Conclusions

1. This paper describes a newly developed technology – the formation of walls automatically using force fields. The science behind acoustic shaping is seen to be well understood.
2. The technology of electromagnetic shaping is as yet in a preliminary stage, with individual elements validated through experiment, and some applications identified in simulation.
3. Electromagnetic shaping is seen as a breakthrough towards building massive radiation-shielded 1-G structures in the general vicinity of 1 A.U. from the Sun.
4. Two extreme strategies are first laid out: a direct mission strategy that sends a set of robots to construct the first stations using a set of radical technical innovations. The other is an evolutionary strategy where various applications are demonstrated on a small scale before taking further steps towards large space stations.
5. Technology elements that are key to these strategies are considered. Pacing elements are identified.
6. The direct mission strategy is cheaper overall for the specific mission of building an extraterrestrial resource exploration station; however, it is hard to build a rationale and public support for a mission of such extreme novelty. It also poses daunting technical risks.
7. The evolutionary strategy is technically less risky, and promises to integrate better with plans for developing a space economy. It runs the risk that focus will be lost, and public interest may not be maintained, for the long duration required to bring it to fruition.
8. A strategy integrating elements of both extremes is developed, and critical pacing items identified. Here the mass is brought by robotic craft from NEOs, but the construction is performed, by assembling small pieces manufactured in enclosed facilities in the Earth-Moon orbital system. The manufacturing facility and the assembly operations can be performed using telepresence from Earth, and the facilities themselves can be constructed out of earth-launched rocket parts such as the STS External Tanks.
9. This architecture is the Extraterrestrial Mass Cislunar Economy (EMCE) architecture. It offers strong advantages in developing manufacturing facilities in space, accelerating lunar development, and setting the stage for human operations in deep space.
10. In the EMCE architecture, synergy is enabled between the acoustic and electromagnetic versions of TFF.

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