Tailored Force Fields for Space-Based Construction:
Key to a Space-Based Economy
Phase 1 Final Report

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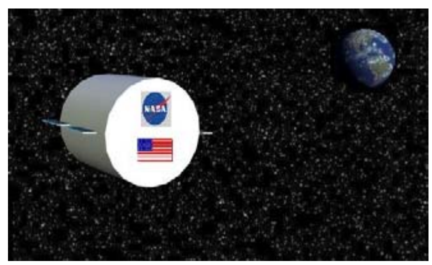

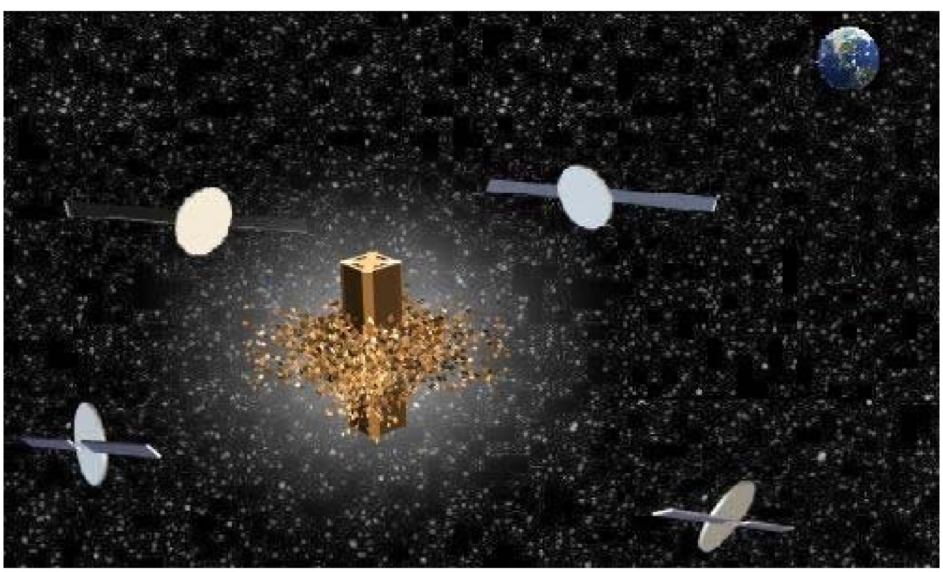

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1. Abstract

Before humans can venture to live for extended periods in Space, the problem of building radiation shields must be solved. All current concepts for permanent radiation shields involve very large mass, and expensive and hazardous construction methods. In this project we consider how such massive structures will be assembled automatically, using at most telepresence or robotic control. A unique set of experiments by our team had shown that by tailoring potential fields, large numbers of objects can be moved into desired positions and desired shapes can be constructed in reduced-gravity environments. Under this project, the promise of this idea was investigated for several types of force fields suitable for automated construction at levels ranging from micrometer-scale discs, to kilometer-scale habitats. The theory for radiation force was generalized and applied to acoustic, optical and other electromagnetic fields. A sample case using silicon dioxide particles of various sizes was used to develop a direct comparison of the accelerations obtainable using different wavelengths of radiation. The feasibility of building objects at the 0.1 m scale using acoustic fields had already been proven through reduced-gravity flight experiments. This was carried forward with experiments being developed for space-flight proof on the STS. A concept for a 50m-scale shield built using radio waves was explored. Calculations show that with developments in extraterrestrial infrastructure, this offers strong potential as a construction technique for the future. Thus the primary obstacle to all of the ideas here is the development of an economic basis for extraterrestrial infrastructure. This was addressed by considering the architecture required to develop a suitable Space habitat in the middle term future. Calculations show that in the 15 - 30yr time frame, a 2km diameter, 2km long cylindrical radiation shield can be built at the Earth-Moon L-2 Lagrangian point using lunar materials and solar-powered quasi-steady electromagnetic fields. The project architecture is aligned with proposals for various other elements of a Space-Based Economy, bringing project cost well within reason.

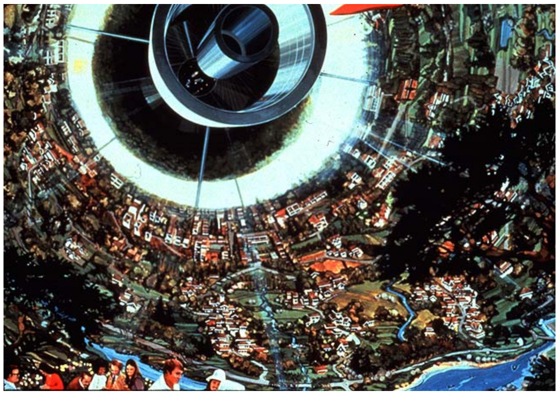
2. Introduction to Tailored Force Fields

2.1 Breakthrough Opportunity

In Space, minor forces exerted over long periods can achieve major results. This fact offers a way to solve some of the basic problems which hinder human ambitions to develop a Space-based economy with permanent, large-scale habitats. In the 1970s, O'Neill [1] and Johnson et al [2] considered the problem of building large habitats in some depth. The well-known artist's conception from the 1970s of the inside of the "Bernal Sphere" habitat is shown in Figure 2.1. Three basic points emerged:

1. Large habitats for a distributed economy were ideally situated in orbit, not on or below planetary surfaces.
2. Long-term human residence in Space required artificial gravity, spin rates below 1 rpm, and most of all, radiation shielding which would stop all ionizing radiation.
3. Human labor for construction would be prohibitive in both hazards and cost.

Given these constraints, there was no practical solution. The mass needed for full radiation shielding was immense, and techniques for assembly of the outer shell and shield of any such habitat demanded millions of human work-hours in unshielded Space.



If a method could be found to build large-scale infrastructure protected from radiation in orbit, commercial activity could accelerate, and the human presence in Space would grow rapidly in a synergistic Space-based economy. The past decades have led to the growing realization that such an Economy is the top priority for Space endeavor. [3,4]

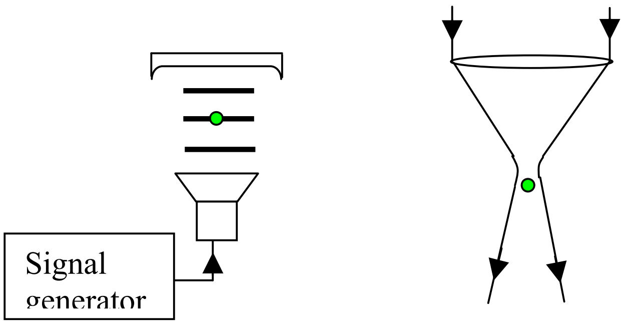
Figure 2.1: "Island One" concept for a spherical colony in Space, described in [1,5]

2.2 Steady and Unsteady Potential Fields

Various kinds of force fields are used today. Forces exerted by radiated energy on objects in their path, have been proposed for space propulsion [6-8]. NASA uses Electrostatic Levitation (ESL) for non-contact positioning involving small particles of some materials. In the vacuum of Space, weak forces acting over long periods, can achieve large results. Familiar examples are microthrusters and solar sails for deep space craft. The relevance of these observations is that automatic construction of large/complex objects from random-shaped material is feasible.

Forces can also be generated by the interaction of unsteady potential fields with matter. In such interactions, the nature of the interaction depends primarily on the intensity and the intensity gradient of the radiation, the transmissivity of the particles for the particular wavelength of radiation, and the ratio of the wavelength to the size of the particle. A beam with a "waist" (focal region) can both "push" and "pull" particles. Very roughly, it may be stated that particles with high transmissitivity get pulled towards the beam waist from either direction – this is used in Optical Tweezers [9-11]. This phenomenon has been explained partly using geometric optics and the refractive index of the particle. The interaction is complex when the particle size is comparable to the radiation wavelength – the Mie scattering regime. In this regime, the interaction of the incident and scattered radiation has a strong directional dependence, and is difficult to compute, especially for non-spherical particles.

Beams are used to position particles, in both optics and acoustics applications. Ultrasonic beams are used to hold small objects (mm scale) away from solid surfaces for non-contact processing. The Optical Tweezer concept is used in microscopy with particles in the micron to nanometer size range. Ultrasonic "Fingers of Sound" are used to hold particles in the millimeter size range in space applications as well as ground experiments. In this NIAC Phase 1 term, McCormack [12] is studying laser beam / particle positioning in orbit to form mirrors for space telescopes.

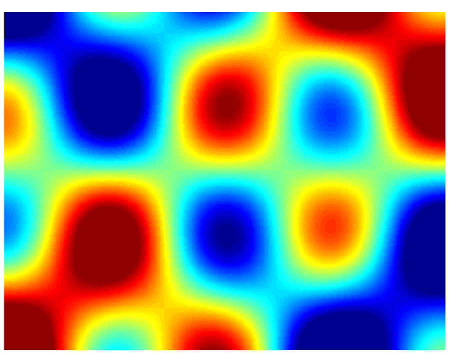


When the particle size is much smaller than the wavelength (less than 0.05 λ) the interaction is described by Rayleigh scattering. Here the scattering is independent of direction, and largely independent of particle shape. It is thus much easier to compute.

Figure 2.2: Stable traps in acoustic and optic fields.

2.3 Resonators

A resonator can be used to increase the intensity of the field by a large factor above that of the incident beam. In a standing wave field, the trapping force can be 1000 times the force obtained with a single beam. The "trapping stiffness" at the stable positions can be seven orders of magnitude above that in the focal region of a single beam. Such phenomena have been considered in detail in the context of optical (electromagnetic) fields interacting with solid particles inside a waveguide in [13]. Figure 2.2 schematically illustrates the creation of a resonant standing wave pattern with multiple beams.



Higher-order modes correspond to complex shapes of the trap regions. This is the aspect which enables the formation of stable walls of desired shape. Figure 2.3 illustrates contours of pressure-fluctuation intensity on a wall of an acoustic resonator.

As mentioned above, with standing waves in a low-loss resonator, small input intensity suffices to produce substantial forces on particles. Various mode shapes can be generated by varying frequency and resonator geometry.

Figure 2.3: Pressure distribution for a higher-order mode in a rectangular acoustic resonator

2.4 Time Line / Application Map

The implications of the above reasoning are explored in a time-line / application map in Figure 2.4. Steady potential fields are commonly used, and have continuing applications for the future. Steady beams of sound and light are already used in positioning small particles, and these will presumably see greater applications in the next few years. The regime of "acoustic shaping" using standing-wave fields offers potential for automated construction of parts ranging in size from millimeters to perhaps 3 meters. This capability can be taken to a technology readiness level for Space Station applications within 5 years, but application to the larger sizes (on the order of 1 meter) must wait until there are facilities large enough to accommodate such manufacture. There is no fundamental obstacle there except the absence of suitable pressurized, enclosed volume in Space – a problem which can be remedied by such solutions as the usage of empty STS main propellant tanks.

At the far horizon is the large size application to building radiation shields for habitats using extraterrestrial material, to form sheltered bases for commercial exploitation of Near-Earth Objects (NEOs). The Near-Earth asteroids will be the most probable source of local mass for building these habitats. Because of the difficulty of obtaining fine-grain material from asteroids, it is probable that the raw construction material will be in the form of rubble of arbitrary shape, with sizes in the range of ten centimeters. Radio-frequency waves will be most suited to move such particles into walls several centimeters to about 2 meters thick for the outer shells of habitats. A set of powerful radio-frequency antennae will be required. While conceptual calculations of the system are possible at this time, credibility demands that we describe the process for initiating large-scale activities beyond Earth, creating a demand for the commercial activity which would justify the building of such habitats.

For these reasons we also undertook the exploration of a system for initiating a space-based economy closer to Earth. Studies in the 1970s (and basic reasoning valid today) showed that the best location for a self-supporting human habitat away from Earth would be in orbit, not at the bottom of the gravity well of a massive body such as a planet or a moon. The need to create a local "artificial gravity" close to 1G, and to maintain a rotation level less than 1 RPM to accommodate the physiological constraints of most humans, dictate the rim diameter of such a habitat – roughly 2km. *The assembly of the massive radiation shield for such a habitat without using large amounts of human labor in Space is the primary challenge.* Thus we looked at the process for creating a 2km diameter, 2km-long cylinder shielded with lunar regolith to a wall depth of 2m, located in the Earth-Moon system.

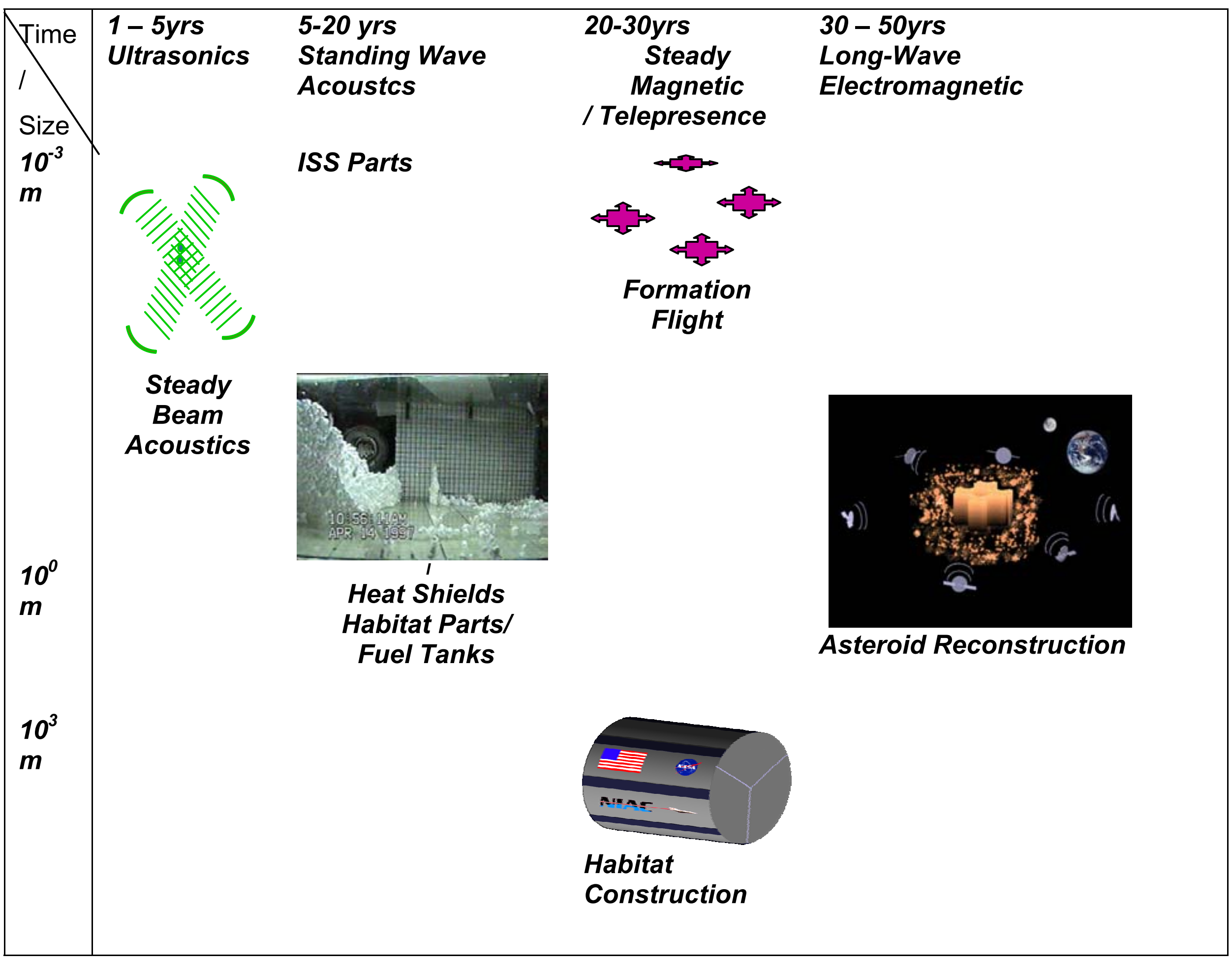


Figure 2.4 Timeline / Size scale and application map for construction using Tailored Force Fields

3. Theory connecting acoustic, optical, microwave and radio regimes

In this section we summarize the development of a uniform view of force field tailoring, generating relations between frequency, wavelength, and particle dimensions.

3.1 Previous work

It is known that optical radiation exerts pressure on solid objects. Solar radiation pressure is significant enough at the orbit of Earth to be included [14] as a low-order effect in trajectory calculations for dust in the vicinity of Earth. When solid particle radius is less than 5% of the incident wavelength, the force exerted on a particle by radiation can be modeled using Maxwell's relations, simplified for the Rayleigh regime [9]. Here the phase differences between radiation falling on different parts of the particle are negligible, simplifying the interference between incident and scattered radiation. In this regime, particles experience a net force in the direction of the incident beam, where there is only one beam, but in the direction of increasing intensity (towards the beam waist) if the beam is focused. Ref.[10] discusses the trapping force experienced on such particles, and shows that *radiation forces can be increased by 3 orders of magnitude, and the "trap stiffness" increased by seven orders of magnitude, when a standing wave pattern is created.* Positioning is improved when the reflected beam from a mirror interferes with the incident beam. Particles move towards nodes or antinodes of the standing wave field depending on their relative refractive index Ref. [13] presents a method for computing forces on neutral particles in an electromagnetic waveguide.

Similar phenomena occur in the field of ultrasonics [15,16]. Beissner [17] discussed models for the radiation pressure in ultrasonic fields from the points of view adopted by Langevin and Brillouin, and compared them in the context of measurements of the radiation force on an absorber at oblique incidence. Collas [18] showed results on acoustic levitation in ground experiments. Yarin et al [19] calculated acoustic radiation pressure using a boundary element method and predicted shapes of levitated droplets, which showed good agreement with experimental measurements. They showed that displacement of the droplet center relative to the pressure node due to the presence of gravity (or other steady force) was significant and could be computed. Wang and Lee [20] reviewed the subject of radiation pressure and acoustic levitation, keeping in view the applications to containerless processing in microgravity. In these applications, ultrasonic frequencies were used, with extremely high amplitudes achieved in the resonator. Zhuyou et al [21] report levels of 183dB inside their ultrasonic levitator used to levitate steel spheres. Refs. [20,22] discuss the issues of acoustic streaming inside these chambers, and their influence on the levitated particles. With ultrasonics, the practical size range of levitated particles goes beyond the Rayleigh regime, and the streaming flow around the particles has a profound influence on thermal gradients, spinning motion, vibration and the ability to retain a coherent trapping force.

We [23] recognized that high sound levels are not necessary, and that acoustic manipulation of objects in reduced gravity would work with audible sound frequencies. In experiments aboard the NASA KC-135 flight laboratory, we showed that positioning worked better when the sound levels were low enough so that the streaming effects were small. Refs. [24-25] extended the flight test results to ground experiments with liquids and powder suspensions. These were the first demonstrations that a multitude of particles inside a resonant chamber would form single-particle-thick walls parallel to the nodal surfaces, and not agglomerate around points of minimum potential.

Our approach in this chapter starts from the observation that the equations describing the generation of radiation forces and trapping stiffness in optics and acoustics are similar. We confirmed this similarity through results from flight and ground experiments using audible sound, comparing them with results from optics and ultrasonics in other wavelength and size regimes. Our results on acoustics show that complex surface shapes can be generated by suitably tailoring frequency and resonator geometry. Predictions for cylindrical and rectangular resonators show that various surface shapes of practical interest can be generated. We generalize these observations to explore the use of long-wave electromagnetic fields to move and position construction raw material in microgravity along desired wall shapes, automatically and gradually, using a continuous input of solar-derived energy. A comparison is developed where particles of the same material are used with optical, acoustic and microwave fields, exploring the power requirements in different wavelength regimes to achieve the acceleration level needed to overcome noise. The comparison is confined to the case of transparent materials in standing wave fields.

3.2 Generalized Relations

From Maxwell's Equations, the undamped electromagnetic wave equation in a non-dissipative medium is:

$$\nabla^2 E - \varepsilon\mu \frac{\partial^2 E}{\partial t^2} = 0 \tag{1}$$

A critical parameter for determining the interaction of radiation with solid particles is the refractive index. In the Rayleigh regime where target particle radius is much smaller than the wavelength ($a < 0.05\lambda$) the particle experiences a uniform instantaneous field due to the electromagnetic wave. Only the electric field need be considered, which makes the problem equivalent to that of an isotropic, homogeneous, dielectric sphere in a uniform field. A spherical target in this size range acts as an oscillating electric dipole. For an incident wave of unit intensity, and transparent particles (refractive index mostly real) the scattered intensity [10] is:

$$I = \frac{16\pi^4 a^6}{r^2 \lambda^4} \left| \frac{m^2 - 1}{m^2 + 2} \right|^2 sin^2 \psi \tag{2}$$

The main feature of Rayleigh scattering in the above is the dependence of the scattered intensity upon the *inverse fourth power of the wavelength*. Total scattered energy can be obtained by integration over the sphere surface. When a wave is reflected off a mirror and a standing wave pattern is formed, there are sharp intensity gradients in the beam. Under these conditions, the two main contributions to the electromagnetic forces acting on the particle in a standing wave field are the Gradient force and the Scattering force. Following [10]:

$$F_{grad}(z,r) = \frac{2\pi n_2 a^3}{c} \left(\frac{m^2 - 1}{m^2 + 2} \right) \nabla I(z,r) \tag{3}$$

and

$$F_{scat}(z,r) = \frac{16}{3} \frac{n_2}{c} k^4 a^6 \left(\frac{m^2 - 1}{m^2 + 2} \right)^2 \frac{P}{w^2} e^{-2r^2/w^2} \left(\rho^2 - 1 \right) \tag{4}$$

The force expressions in the electromagnetic field are similar in form to those in the acoustic field, for the moderate-intensity, Rayleigh regime of acoustics where acoustic streaming and the generation of harmonics by nonlinearity are secondary. The electromagnetic fields do not offer mechanisms for the generation of such nonlinearities in their simple form, though such effects cannot be ruled out when interaction with large numbers of particles is considered in detail. Parameters may be compared roughly as shown in Table 3.1. While small, the acoustic field numbers in Table 3.1 are seen to be adequate [24] to rapidly form walls with various types of particles, even in the presence of g-jitter of the order of $1 m/s^2$.

Table 3.1. Important Parameters and Magnitudes: Comparison of Optics and Acoustic Force Fields.

Parameter	*Optics*	*Acoustics*
Stress term	Maxwell's stress tensor	Radiation stress tensor
Rayleigh regime size	Nanometers	Millimeters to centimeters
Material parameter	Ratio of Refractive Indices of Solid to medium(or vacuum)	Density ratio of particle to medium
Intensity	Optical intensity	Sound pressure fluctuation intensity
Force order of magnitude	Zemanek, Re.[10]: 514.5 nm laser; beam waist of 8 microns; 5nm glass sphere in water; Force = 2.5 *10^{-22} N.	Wanis[24]: 156 dB at 800 Hz (1 0 0) mode at 2mm radius rigid particles. Force = 3.3*10^{-6} N

3.3 Development of a common basis for comparison across wavelength and particle size

In Figures 3.1 – 3.3, this comparison is extended to a standing microwave field to get a different range of wavelength and particle size. In this first consideration of the generalized problem, we used the following logic to enable a direct comparison of different types of waves and particles, drawing upon each application area. Optical tweezers usually use visible wavelengths and the theoretical expressions are simpler for transparent particles (glass, which is mostly silicon dioxide). Microwaves transmit through silicon dioxide, and acoustic shaping works on most materials. This enables us to choose material of the same density (roughly 2000 kg/m^3), and assume the refractive index of glass relative to vacuum for both the optical and microwave cases. In Figures 3.1 – 3.3, the force per unit incident radiation intensity is divided by particle mass to obtain the acceleration per unit intensity. In the case of gradient forces, the gradient is approximated by dividing the intensity by a quarter-wavelength (Chapter 7 includes a more refined calculation which justifies this). The abcissa is the particle radius. For each particle radius, the wavelength used is 20 times the particle radius to stay within the Rayleigh regime definition and remove some of the wavelength dependence. The acceleration in each case depends inversely on particle radius. This poses a drawback in dealing with raw material until powerful long-wave resonators can be developed, or we learn to generate adequate coherent forces in the Mie scattering regime.

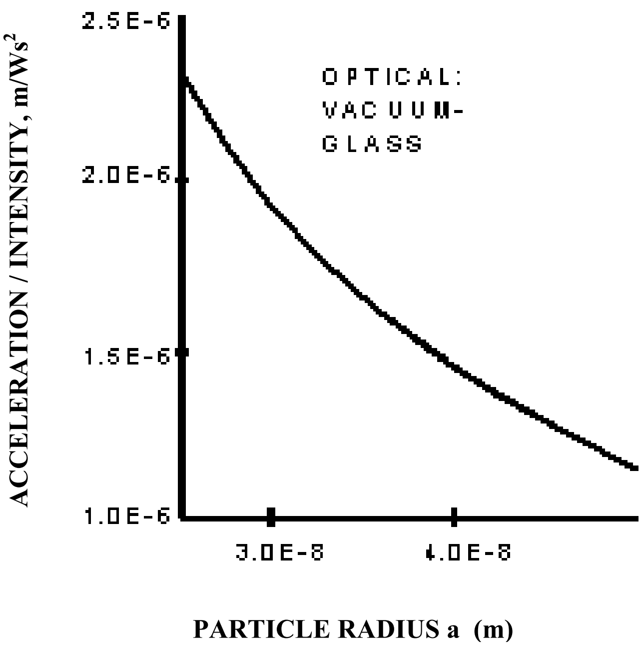


Figure 3.1 Estimate of the acceleration per unit intensity, experienced by glass spheres in a standing wave field of optical radiation in vacuum, with the radiation wavelength being 20 times the particle radius.

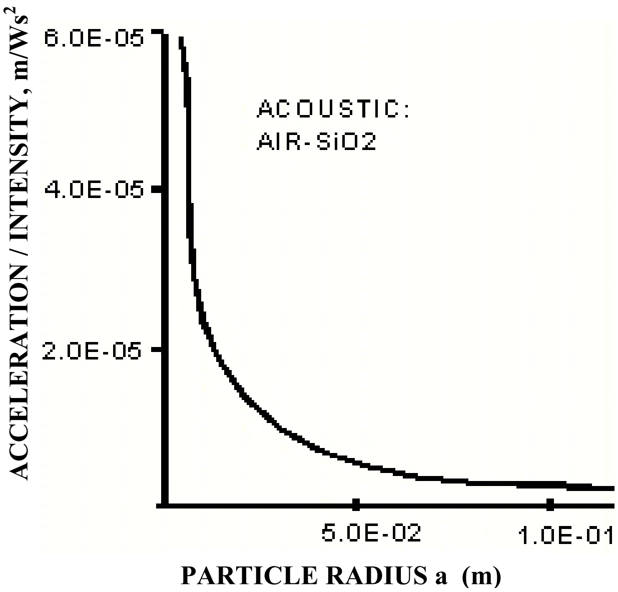


Figure 3.2 Estimate of the acceleration per unit intensity, experienced by silicon dioxide spheres in a standing wave field of acoustic radiation in air, with the radiation wavelength being 20 times the particle radius.

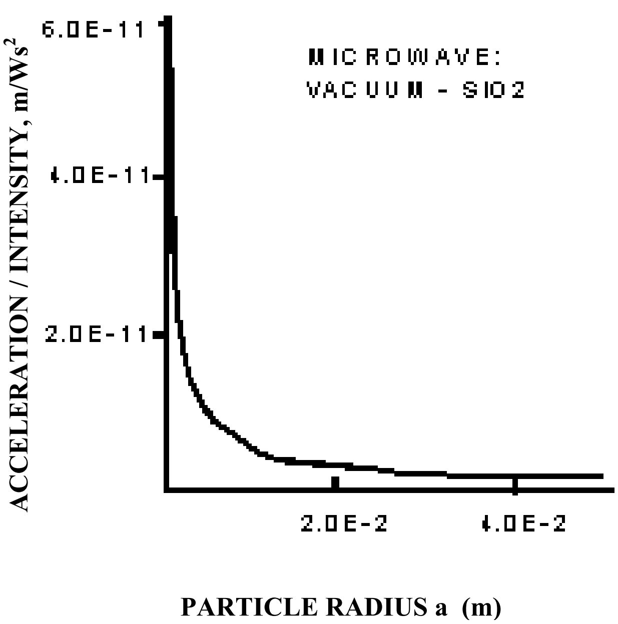


Figure 3.3 Estimate of the acceleration per unit intensity, experienced by silicon dioxide spheres in a standing wave field of microwave radiation in vacuum, with the radiation wavelength being 20 times the particle radius.

To-date, as seen from Table 3.1, the Rayleigh-domain experimental data are in the acoustic regime with millimeter-scale objects [23-35] and the optical regime with nanometer-scale objects [10]. The above results indicate that high microwave intensity would be required to move particles. It is a good rule of thumb that intensities achievable inside resonators can reach 3 orders of magnitude higher than source beam intensity. Our experiments on acoustic shaping (below) show that 40kW/m^2 corresponding to the 156dB resonant field shown in [24] is adequate for forming walls from ceramic materials in acoustic resonators. In the optical regime, the values of acceleration per unit intensity are 1 to 2 orders of magnitude lower than those in the acoustic case. As the wavelength (and hence the maximum particle size considered) increase, the acceleration per unit intensity decreases in inverse proportion. However, the feasibility of generating high power improves rapidly, and the cost of power generation at the desired wavelength decreases. For example, infrared lasers achieve 1kW routinely for far less cost per watt than, say, a visible-range laser.

Going into the microwave regime, we see that the values of acceleration per unit intensity are 6 orders of magnitude below those in acoustics. We have no experimental evidence so far of particles being positioned using microwaves; however, JPL's web pages speak of a microwave sail being developed, as an extension to solar sail technology. Clearly, microwave intensities needed to produce significant acceleration, will be quite large. Microwave beam intensities up to 8MW /m^2 have been demonstrated in ground-based laboratory experiments [26]. With a resonator Q-factor of 1000 for short-duration operation in a wall-formation application, we may thus expect to achieve microwave resonator intensity in space experiments of 8GW/m^2. It thus appears reasonable that microwave-induced electromagnetic shaping using raw materials such as silicon dioxide (primary component of lunar regolith) is feasible in prototype experiments where we can use closed, metal-cased enclosures.

4. Acoustic Shaping

4.1 Prior Results

In the preceding sections we showed that significant forces could be generated in unsteady fields, especially standing wave fields, due to interaction between the field and solid (or liquid) particles. Comparison of optical, microwave and acoustic forces shows that significant accelerations, much higher than the disturbances from "g-jitter" in orbit, can be achieved using all three kinds of waves. In the following section, we show flight validation of the idea of using such forces in a resonant field, to form prescribed shapes of walls. Acoustic shaping in reduced-gravity experiments is used, since an opportunity provided by NASA on their Reduced-Gravity Flight Laboratory made this feasible. *These results were obtained before the present NIAC grant;* however, they are reproduced here to emphasize that constructing predictable shapes is valid and practical.

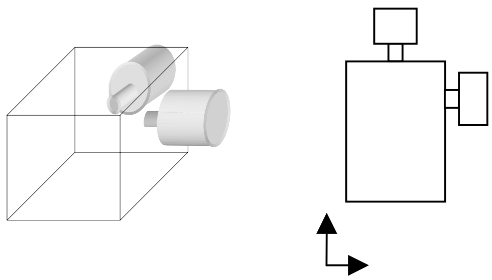


Figure 4.1 Rectangular chamber geometry used for reduced-gravity acoustic shaping experiments [23-35]

Wanis et al [23] used a rectangular plexiglass box with speakers mounted on two sides across a corner as shown in Fig. 4.1. Only the speaker in the end face was used. With solid particles placed inside the box, the setup flown in reduced gravity, and the speaker driven at a natural frequency of the box, the particles migrate rapidly and stand along the nodal planes of the box (Figure 4.2.)

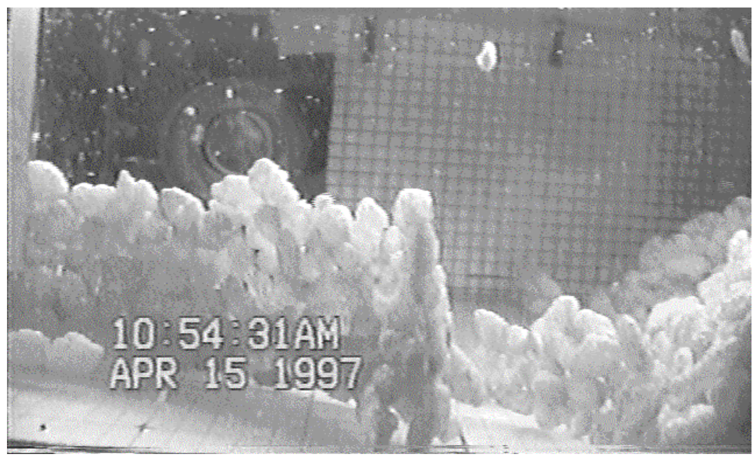
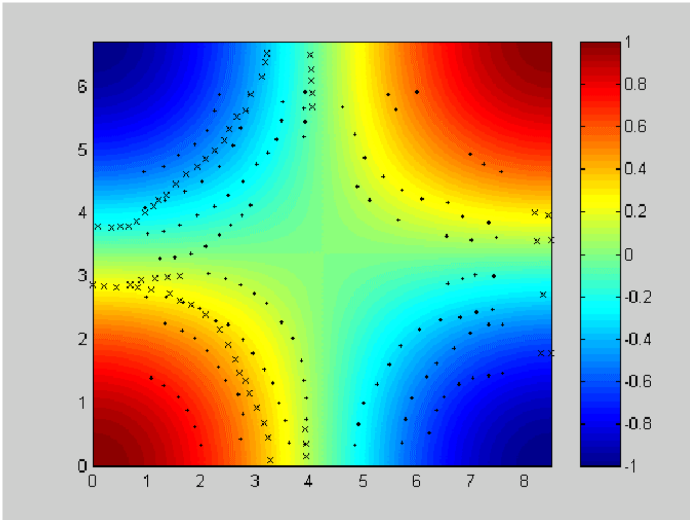


Figure 4.2 Single-particle thick walls of irregular ellipsoidal grains, forming parallel to the nodal surfaces in reduced-gravity flight experiments

This is a crucial demonstration: in the ultrasonics and optics experiments performed elsewhere, the primary interest was in holding one particle close to a pre-selected point of minimum potential. Here it is seen that when a multitude of particles are placed in a resonant potential field, they migrate, not to the single point of least potential, but to fill entire surfaces. These are thus self-forming walls – videotapes of the flight tests show that the particles "jostle" each other and fill up vacant spaces in the walls. The clarity of the video frame shown above confirms our observation that the walls are stable, and irregular-shaped particles stay fixed in position, with no rotation or vibration.

The environment where the above results were obtained is shown in Fig. 4.3. The frequencies and gains were set by the experimenter with the cap (Andres Sercovich) while their values were read out by his teammate (Ron Sostaric). There was no feedback control or correction for differences in air temperature between the ground experiment and the flight test. The best results (stable walls) were obtained when the input intensity was quite low – so that secondary effects such as acoustic streaming were not strong.

Figure 4.3 Experiment on board the NASA KC-135 Reduced-gravity flight laboratory where the image in Figure 4.2 was obtained



Various other results have been obtained on such wall formation – these are reported in [23-25]. The mode shapes even for a rectangular container can be quite complex, and the measured locations of the walls are parallel to or coincident with the nodal surfaces. Figure 4.4 shows comparison between predicted and measured wall locations, with the measurements being made in ground tests where particles arranged themselves along the floor of the chamber.

Figure 4.4 Measured locations of Styrofoam particles along the floor of a rectangular resonator operated at its 1 1 0 mode in a ground experiment.

In Figure 4.5, we see that the walls do not touch the walls of the resonator, but extend close to the walls. Also, the formation of large walls along the nodal surfaces does not alter the sound field enough to shift the resonance to another frequency. Figure 4.6 is one of several flight test results showing the formation of walls with hollow aluminum oxide spheres (white) mixed with hollow aluminum spheres (shiny metal).

Figure 4.5 Walls of Styrofoam particles form in an acoustic resonator operated at its 110 mode. Reduced-gravity flight test, April 1997.

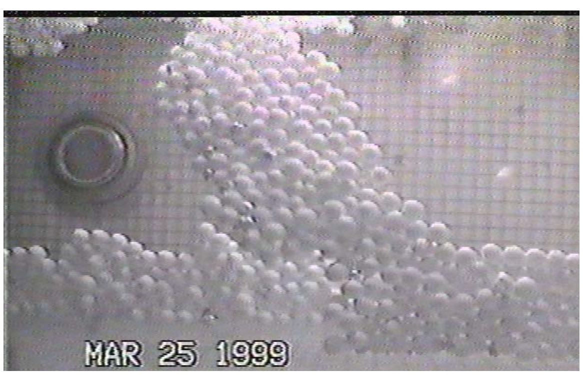


Figure 4.6 (below, left) Walls of hollow aluminum oxide spheres and hollow aluminum spheres. Flight test, acoustic field.The walls are usually 1 particle thick. The small aluminum particles are seen to occupy the space between the larger aluminum oxide particles.

One issue that has come up in previous Acoustic Positioning experiments in Space is the ability to hold particles still as the temperature field around them alters. Wang et al [20] note that interaction between the streaming flow and the thermal boundary layer of a heated particle would reduce or even reverse the trapping force in the standing wave field, and hence cause the trapped particle to drift away, as it cools following melting in an oven. This effect occurs in the Mie scattering regime, where the interaction between the incident and scattered radiation has a strong directionality. When audible-frequency sound and millimeter-sized particles are used, the interaction is in the Rayleigh scattering regime, and such problems are much less significant. Figure 4.7 is a preliminary attempt to demonstrate that a wall formed of molten particles can be cooled without the trapping force being destroyed. The material in this case consisted of millimeter-sized balls which were heated to the melting point, then placed in a resonant acoustic field and allowed to cool, with the frequency continuously changed to accommodate changes in speed of sound. This experiment was performed in the lab in 1G, so the wall is not very high. The particles remained in a vertical wall until the material solidified, forming the first solid object built in an acoustic field.

Figure 4.7 T-shaped object solidified from molten millimeter-sized balls of Agarose, with the driver frequency continuously varied to maintain resonance during cooling. Ground experiment in 1G

The above experiment demonstrates that liquids will form into walls along the nodal surfaces in a resonant acoustic field in 1-G. Thus the nodal regions are clearly regions of low static pressure, in addition to being the trap region for small particles. This interesting discovery was investigated in forming walls of water in 1-G. It was found that the walls would shatter at the top, with a spray of droplets escaping, causing a fountain effect as more water was pushed up into the wall from below. When a powder was suspended on the water surface, the sheets remained much more stable, and steady walls of water with suspended powder were formed, again with very small thickness. We have not measured the thickness, but it appears to be of the order of a millimeter. Examples are seen in Figure 4.8.

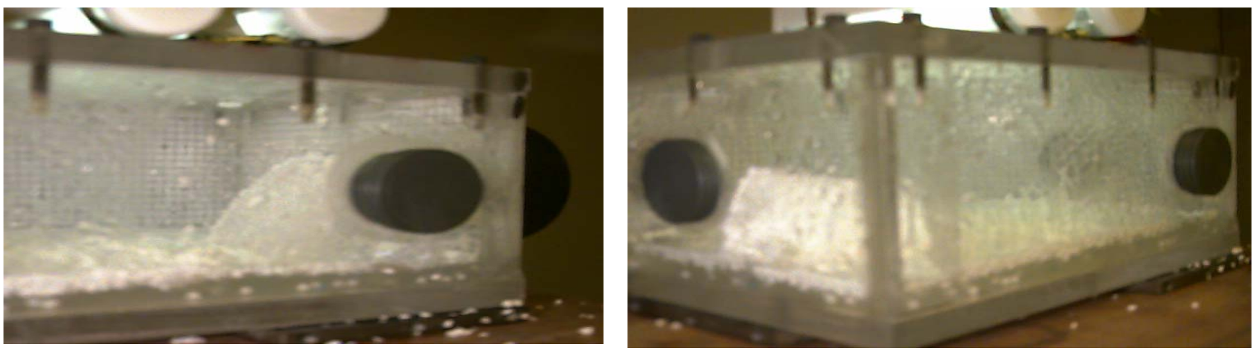


Figure 4.8 Curved (quarter-spherical) walls of water with suspended powder, formed in an acoustic resonator. Ground test, 1-G.

4.2 Implications of the Acoustic Shaping Results

From the above experiments, it is clear that acoustic fields can be used with solids, liquids and phase change, to form solidified objects with thin walls, in reduced gravity. The height of liquid walls can be much greater, with a different choice of acoustic medium, static pressure, and g-level, offering the potential for various manufacturing processes in lunar or artificial / variable- gravity stations. An example of such a process is conceptualized below in Fig. 4.10: A solid object is built in several parts in an acoustic field, with processes involving solar-powered heating, cooling and robotic assembly. Objects up to about 3 meters in size can be built with conventional technology using appropriate gases, provided that large chambers can be provided in reduced-gravity environments.

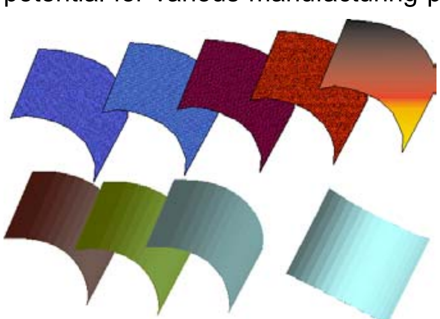


Figure 4.10: Formation of a part of a cylindrical object using acoustic shaping, with color and texture changes indicating temperature variations and change from granular material to solid-walled part.

4.3 Development of Shape-Design Software for Tailored Force Fields

By combining several modes, with variable amplitudes, various interesting shapes can be built. To visualize these and permit experimentation, a software package was developed, using Matlab. Currently a more user-friendly, stand-alone version of this, suitable for use by non-technical personnel, is being developed. Results from our experiments with this software are shown below in Figure 4.11. The software can be modified to simulate other types of radiation such as microwaves or radio waves quite readily.

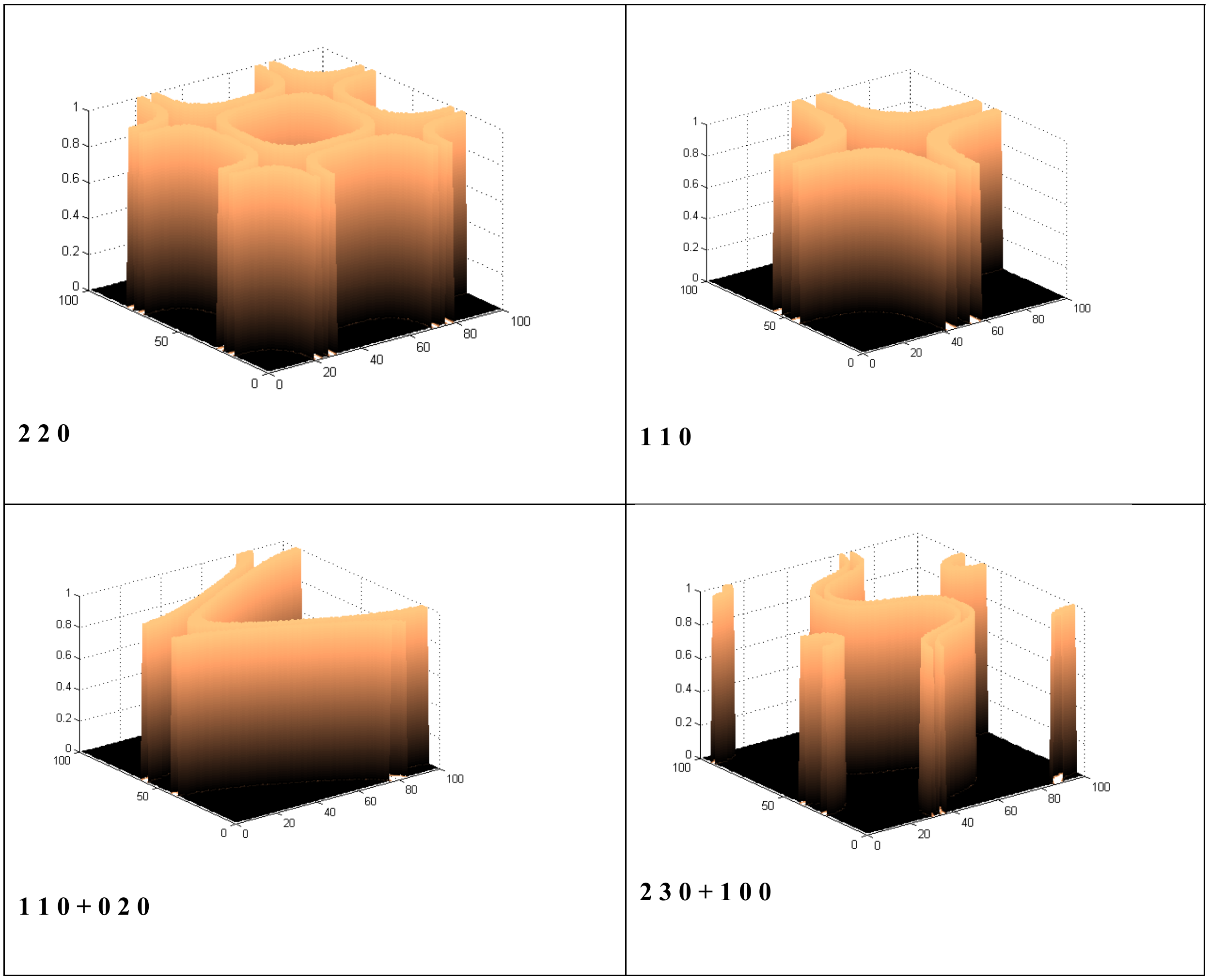


FIGURE 4.11. *Simulation results on useful wall shapes combining low-order acoustic modes in a rectangular chamber.*

4.4 Concluding Remarks on the Findings in Section 4.

In this section we have presented the idea of tailoring unsteady potential fields to form solid particles of arbitrary shapes into walls of prescribed geometry. We have considered applications and theoretical results from optics and acoustics to show that the force generation mechanisms bear similarity. Choosing a material with a wide range of forms, but generally uniform density (silicon dioxide as glass and regolith) we have performed a direct comparison of the particle accelerations achievable using optical, microwave and acoustic standing wave fields. Experiments using acoustic shaping confirm that particles of arbitrary shape migrate rapidly to nodal surfaces whose shapes correspond to simple predictions. Generalizing using the similarities between different wave fields, we conclude that electromagnetic shaping could become a viable option to consider for automatically forming useful objects in Space, when high-power, long-wave resonators are developed.

There are, no doubt, complexities in building refined parts using acoustics. There is a rich body of literature on the theory relating to ultrasonic positioning. Liquid manipulation using acoustics is also a topic of strong research interest [27]. The issue of driving multiple resonances is dealt with in [28]. However, the experimental results shown here are proof that the basic concept is feasible and worthy of further exploitation. The major breakthrough in our work is the confirmation that tailored force fields of various types of radiation can be used, with essentially similar and predictable characteristics. This permits excellent simplifications in our view of what appeared at first sight to be an intractable problem.

While the formation of parts by acoustic shaping is feasible today, acoustic shaping requires containers with gas atmospheres. The formation of walls and useful shapes from microwave and other electromagnetic radiation can be performed in vacuum, but require substantial power sources, and will become realistic when there is a movement towards the construction of large power sources such as solar power satellites or power beamed from the Moon. For any large-scale construction in Space, massive resources from extraterrestrial locations (Moon or asteroids) are essential. Large-scale extraction of extraterrestrial resources requires an economic framework with long-term payoffs. In following sections we discuss an architecture for building the first massive human habitat at the Earth-Moon L-2 or L-5 regions, as part of a coherent plan for a Space-based economy. The project is conceived as a synergy between concepts for lunar-based solar power plants, lunar robotic mining and metal processing, robotic fabrication plants, and a set of electromagnetic launchers as a lunar equatorial space launch systems. Railcar-sized rectangular containers filled with 2m thickness of lunar regolith (dominantly SiO_2) are launched off the lunar surface. They are captured in space by “shepherd” space tugs which guide them to the axis of the cylinder, and positioned using an electromagnetic grid onto the outer cable grid of the cylinder, before being robotically fixed to each other. A quasi-steady magnetic positioning and assembly technique is used in this process.

5. Task Report : Intermediate Term Architecture for a Radiation Shielded Habitat

The purpose of this NIAC project is to look at concepts for building large-scale habitats in orbit. While that is clearly several decades in the future, it is necessary to lay out a possible path to get there from the present. At the outset, we point out that our interest is more in laying out a path to build massive habitats using automatic, low-recurring-cost techniques, than to get into the “Moon vs. Mars” debate, and hence our choices are not necessarily optimal – it is enough for our purposes to show what it takes to make them feasible. The work described in this and the following chapters was in fact motivated by a question from a NASA engineer in the audience at the First Space Resource Utilization Roundtable in 1999 – *“how will you build one of those massive colony shells using your automatic techniques?”* We considered techniques that would work in vacuum – and of course, quasi-steady magnetic fields are the most obvious choice there. In this chapter we discuss the intermediate-term architecture, which involves considerations of education, economics and pubic support, in addition to engineering. To chart this path, we present a technique to build one of the grandest projects envisioned in the 1970s – the first large habitat beyond Earth. In 1975, Gerard O’Neill presented his concepts for the first habitats, to be built at the L-5 point of the Earth-Moon system. Features of the O’Neill habitat [1] concepts are summarized below:

5.1 O’Neill / NASA 1970s Model for Habitat

- Economic opportunities as motivator. The precise industries foreseen as the leaders of this enterprise may not today be the prime movers, but the basic concept that economics - rather than exploration or national / military motivations - would drive the construction of the habitat, remains valid today.

- Moon as first source for extraterrestrial resources. The Moon was seen as the logical first place for the extraction of resources such as oxygen and metals. This choice remains valid today, since there is far more quantitative knowledge about the composition of lunar soil, and the availability of various resources, than there is about any other heavenly body. O’Neill pointed out that much of the material processing might actually be done in the habitat itself, where varying amounts of artificial gravity would be available.

  Today this choice triggers considerable argument, which is driven by the perceived need to make either/or choices between the Moon, the Near-Earth Objects, missions to Mars, and missions beyond Mars. However, we present this as the first step in the systematic development of infrastructure on the scale needed to enable the realization of all these dreams. In that context, O’Neill’s choice of the Moon as the best-understood destination is still valid.

- L5 as the logical location for the settlement. The argument for a habitat in Space, rather than on the Moon, was that the economic reasons for the habitat involved access to other locations such as GEO, to service other satellites and Space Stations, and provide access to Mars and beyond. The access cost would be greatly reduced by locating the habitat in orbit rather than in a “gravity well”.

  Again, this is a choice which triggers much debate. Concepts for developing radiation-sheltered sub-surface habitats have been developed (e.g., Boston [29]) and offer attractive options for quick and relatively inexpensive development of sophisticated long-term habitats with controlled atmospheres. These will be attractive, and indeed essential, for resource-development operations on planetary and lunar surfaces. However, the argument about access to multiple points in Space holds today. The major advantage of a sub-surface habitat is that there is no need to transport huge amounts of material into orbit to construct a radiation shield – and until now this was a clincher. With the concept that we present below, this is no longer a clincher. With our concept, the facilities developed to build the radiation shield in orbit will remain as permanent facilities for lunar transportation and manufacturing, and reduce the marginal cost for shield construction by several orders of magnitude. The advantages of variable-gravity facilities for manufacturing are strong additional arguments for a Space habitat.

- “Bernal sphere” + toroidal agriculture stations on either side, with near-1-G at the equator. Studies existing at the time were cited for evidence that long-duration exposure to low gravity would harm the health of humans. This has since been corroborated by experience with the Mir station. In addition, studies were cited to the effect that over 3% of humans would find an angular velocity of more than 1 revolution per minute to be disorienting. To achieve a gravity level of 1G, with less than 1RPM, the habitat would require a radius on the order of 1 kilometer. Various shapes of habitat were considered in a NASA-ASEE study in 1975-77 [2]. Toroidal habitats were selected. Examination of the reasons for picking the toroid shows that a cylindrical shape would have been better, but was considered unnecessary because it would offer far more than the required surface area to support 10,000 inhabitants. *Thus the toroid chosen must be viewed as a minimum-length cylinder.*

- Shell made of aluminum and glass (to admit sunlight); support structure made of aluminum ribs and/or steel cable. This was based on then-prevalent construction techniques for lightweight, mobile structures. Human labor was assumed, in order to not make assumptions about the availability of robotic machines. The aluminum and glass were assumed to be shipped from the Moon initially, and from orbital manufacturing facilities for subsequent construction projects. We avoid the need for such detailed construction, and present a system amenable to automatic construction.

  Our construction sequence, summarized below, involves deploying several rings of metal cable, attached to solar-heated gas thrusters which will provide a small rotation rate to provide some tension and retain a circular shape. Rectangular metal containers (boxcars) of size 20m x 2m x 2m will be launched from the Moon to arrive at this site with a very low apogee velocity. They will be maneuvered into place using hybrid “shepherd” spacecraft, and welded together using robotic welding arms. The final stage of the maneuvering, which is the actual construction stage, will be performed by interaction between electromagnets on the Shepherds, and currents in an electric grid held by a construction Spider, a robotic platform. A ring of these containers will provide the nucleus of the structure. A central beam structure will be built along the axis as the nucleus of the zero-g manufacturing facility. A mobile “construction spider” and a tether system from a central metal structure, will be used to reduce the repetitive work in capturing and positioning loads. Additional cable rings will be attached to the first ring of boxcars, and used to support the next set of boxcars, and so on. The angular rotation rate will be maintained, and gradually increased, by gas thrusters. After the first ring of boxcars is completed, following boxcars will arrive filled with lunar regolith to form the radiation shield. As the 2km-long cylinder is completed, the ends will be sealed using a combination of water-filled inflatable bags, support structure, solar collectors and transportation gateways. It is not considered necessary to enclose (other than for radiation shielding) and pressurize any part of the cylinder except those regions intended for human or other live occupation (e.g., agriculture sections). The agriculture sections may be in concentric cylinders at much lower g-levels closer to the axis, with filtered sunlight directed in at appropriate angles using thin-film mirrors.

- Projected earth-LEO launch costs of $110/lb. Costing was attempted, assuming this launch cost to Low Earth Orbit using the as-yet untested Space Shuttle, with boost to the lunar L-5 requiring the same amount of energy again. While this number proved to be an underestimate by two orders of magnitude, the implication now is to rule out the use of Earth-launch for any recurring-cost or mass-manufactured items that can conceivably be manufactured on the Moon or in orbit. It is still necessary to Earth-launch such items as control equipment, the spacecraft needed to shepherd loads to the construction site, hydrogen, nitrogen, and the robotic arms for manufacturing on the Moon and at the habitat site.

- Lunar-based mass driver. The bulk of the material for the radiation shield, which was to be built of lunar regolith, was to be launched fire as baseball-sized lumps of regolith, accelerated at 30G over a 10km track, and at a rate of about 10 per second. A “catcher” system positioned near L-2 would receive these ballistic payloads and “take” them to the construction site. We depart from this launcher, which was optimized for the single project of building a habitat, and instead argue for a versatile launcher system which will form the nucleus of the future translunar surface transport system. Our basic payload unit is a 160,000 kg “boxcar” filled with regolith, launched by a carriage which keeps the electromagnetic components of the launcher on the Moon for re-use.

- Radiation shielding dominated the mass of the settlement. Ref.[2] envisaged a stationary radiation shield around a revolving toroid, with some means for maintaining a suitable gap between the shield and the moving structure. This was seen to greatly reduce the strength demands on the spokes and other structure of the habitat. In our concept, we use metal cables to provide the initial scaffolding, followed by a welded-box rib and longtitudinal beams for the shell strength.

5.2 Present Model of a Habitat

We adopted a strategy whereby the habitat project would itself serve to bootstrap an entire Space-based economy. Rather than optimize everything for the most efficient construction of the habitat, we looked at how to set up the many other industries in a synergistic economy. Our approach also assumes that human presence at the construction site is not necessary until the radiation shield is complete. Recurring costs are minimized, and thus the project can be spread out over a longer period. Since the construction is automatic (with at most telepresence supervision and control from Earth) we can afford to consider building a cylinder 2km long, with the entire radiation shield gradually accelerated to 1 RPM by the time the shield is complete. Major differences with the 1975 approach are summarized in Table 5-1.

Table 5.1: Important Differences Between 1975 and Present Models for Space-City Construction

#	1975 models	Present model using Tailored Force Fields (TFF)
1	$110/ lb Earth- LEO	$1,300 to $14,000 per lb to LEO
2	Human labor on-site	Robotic with Earth-based telepresence supervision
3	Geometry: Toroid with non-rotating shield.	Cylinder with flat or hemispherical end-caps for radiation shielding.
4	Construction at L-5	Shell construction at L-2 followed by slow move to L-5
5	Lunar H_2-powered mass driver. Baseball-size loads. 30g; 10km run [2,30]	Lunar-equatorial Solar-power fields, 20 launchers; round-the clock launches; fuel is lunar-generated electricity. Railcar-sized loads. 8-g, 40km track.
6	Entire interior pressurized.	10 to 30 meters at rim pressurized, using membrane with 30-meter bubbles to provide micro-climates.
7	Machinery required to make panels etc.	Non-contact shape formation with solar-heated powder sintering & furnaces. Robotic assembly of payloads.

5.3 Choice of Construction Location

The Earth-Moon L-2 is chosen over L-5 as the construction location to minimize the lunar launch energy. The final move from L-2 to L-5 (if needed) could be done by gradual orbit transfer over a period of months, with solar-heated gas thrusters providing the energy. The choice between Earth-Moon L2 and L1 is somewhat arbitrary – strong arguments could be made for locating the station at L-1. Either location is convenient for telepresence operation from earth – satellites in GEO or at L-4/L-5 can serve as convenient observation platforms. Launches to L-2 would usually occur from the visible side of the Moon – which will be more convenient for initial operations. The resource extraction facilities on the Moon, including the lunar solar-power fields and power-beaming plants, are more likely to be located on the visible side, so that the first launchers will be built on this side as well. Hence the choice of L-2.

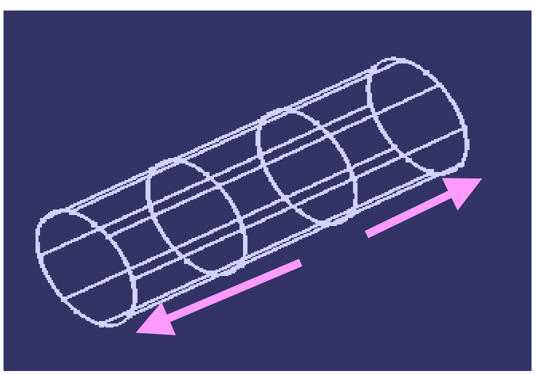
These issues have been studied in the past in detail. Heppenheimer and co-workers [31-33] evaluated over 48,000 test trajectories to obtain all achromatic trajectories from the moon to any of the earth-moon libration points L1, L2, L4, L5, as candidate sites for a mass-catcher to receive material launched from the moon. They found ten such achromatics, and gave their characteristics and a photographic atlas of their launch sites. The best transport mode found was to launch from Mare Tranquillitatis to L2, with the mass-catcher maneuvering near L2; acceleration of the mass-catcher due to momentum transfer from the "mass-stream" was considered. Three propulsion modes were considered: ion-electric, Rotary Pellet Launcher, and Advanced Space Engine. A reference catcher design was proposed. A critical launch longitude was shown along the lunar equator (33.1 deg E) for a certain class of trajectories to L2, to "minimize the dispersion such that a miss distance of lunar materials at L2 of 50 m would result from launch velocity errors of approximately 10 cm/sec along the track, 1 mm/sec vertically, and 1 cm/sec laterally" [31]. The acceleration requirement for the mass catcher to follow lunar librations was 1.5 E-4 m/s^2, plus modest additional stationkeeping with respect to the local force field. In the O'Neill system, the manufacturing facility was located within a ΔV of 10 to 30 m/s from L-2.

Optimal launchers for the O'Neill system had the constraint that they were powered by gas or nuclear energy, either option requiring large earth-shipped mass to operate. Their model imagined most of the regolith processing to occur inside the "manufacturing facility" part of the habitat – so there was little incentive to develop other infrastructure on the moon. These considerations drove their optimum solution to be one where a stream of mass, sized to approximate baseballs, would be accelerated at 30gs by a 10km accelerator track [33]. It made sense there to build a complex "mass-catcher" and transport the mass to the "manufacturing facility".

In our model, we make use of other people's motivations to build infrastructure on the moon, and design our habitat project to enable all such projects to become realities. Thus in our system, there can be multiple launchers, distributed around the moon's equator, and accordingly, multiple solar-power fields, power plants, mines and metal processing sites. Thus our launchers are part of a permanent lunar export infrastructure, with dual-use as the nucleus of a lunar surface transport system. We also need metal box beam structures shipped to the construction site, to form the outer shell of the cylinder. These metal structures, accordingly are built as containers for the regolith. With the number and frequency of regolith launches greatly reduced, it makes sense to have a few "Shepherd" spacecraft performing the triple functions of (a) mass-catcher, (b) transporter to the construction site, and (c) maneuvering the loads into position as the assembly of the structure. Interlocking appendages on the containers enable much of the structural loads to be carried before the boxes are welded together by robot arms.

5.4 Construction Sequence

Cable Grid Deployment and Construction "Spider".



The first 4 boxcars will be launched in quick succession, empty except for eight cables – four for the first set of cables, and the rest for the second set. A hub beam structure and a "construction spider" equipped with an autonomous power supply, an electromagnetic wire grid, four robot legs with grapplers, and a robot welding arm, will be brought from Earth and positioned by the "shepherd" craft. The first four rings of 12.5mm dia. cable segments, 1km in radius, spaced 4 meters apart, will be connected by longitudinal cables. The cable rings will be started in rotation by thrusters. The tension is kept low until first boxcar ring is complete. The dynamics of cable grid deployment in orbit require further analysis.

Figure 5.1 Deployment of initial cable loops for the cylinder construction project

Regolith Transport and positioning

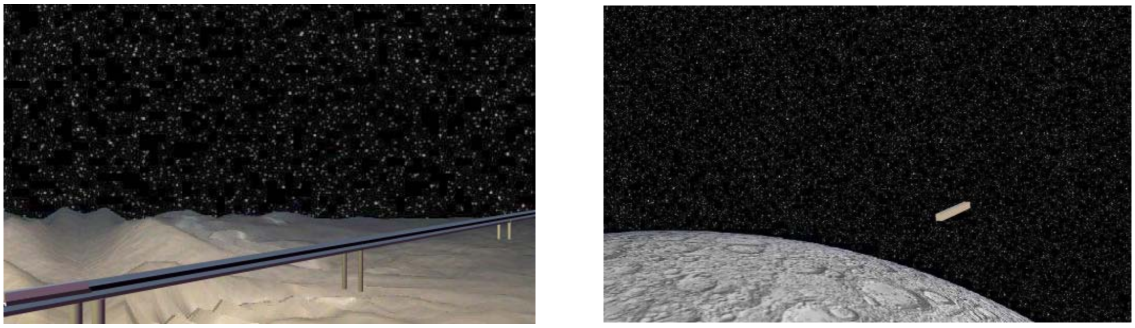


Figure 5.2 Boxcar launched off the lunar surface in an orbit with apogee at L-2

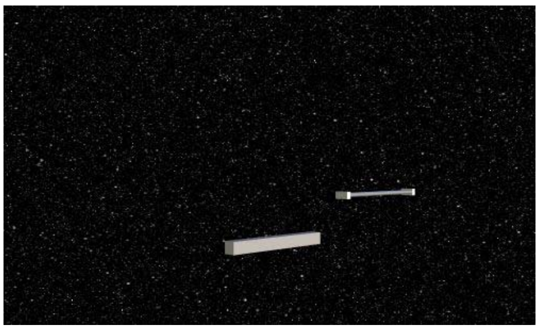


Figure 5.3 Rendezvous with "Shepherd" craft

Lunar regolith 2 m. deep is brought up in iron/steel railroad boxcars. Each boxcar is met by a "Shepherd" craft. Each regolith-filled "boxcar" is brought by a hybrid gas/ e-mag "shepherd" craft, and guided towards the grid. Each arriving load-train is captured by a winched tether attached to the rotating grid. Axial momentum is transferred to radial and tangential momentum, bringing the load to the periphery at 1kmph, into the space between the outer grid and an active, powered electromagnetic "Spider" construction grid. Electromagnetic interaction between the loads, the construction grid, and the shepherds, moves the loads into position against the outer grid. The shepherds leave the grid. Robots attached to the construction grid complete the attachment of the box-cars. Figure 5.5 shows a load arriving, attached to an electromagnetic Shepherd, aimed by the tether into the space between the Spider and cables. The currents in the grid held by the Spider interacts with electromagnets on the Shepherd, making the final adjustments and maneuver the boxcar into place.

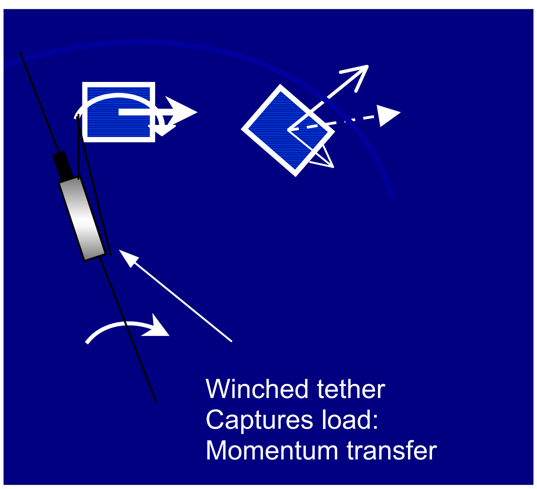


Figure 5.4 Load is captured by a tether at the entrance to the cylinder grid, transferring axial momentum to tangential and radial momentum

The Shepherd detaches from the boxcar and pushes off from the cylinder site, to return to lunar orbit for the next rendezvous. The Spider is a robot, which can attach its legs either to the cables or to already-positioned boxcars. A set of welding arms on the Spider fixes the boxcars to each other. Note from Fig. 5.6 that the boxcars are built with interlocking wall geometry, so that the tensile load on the cylinder rim is transmitted through the interlocking structure, not through the welds.

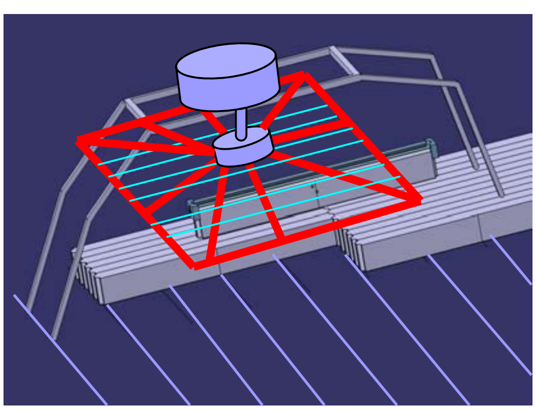


Figure 5.5. Regolith-laden boxcars being delivered by "Shepherd". Shepherds maneuver boxcars into place using e-mag field.

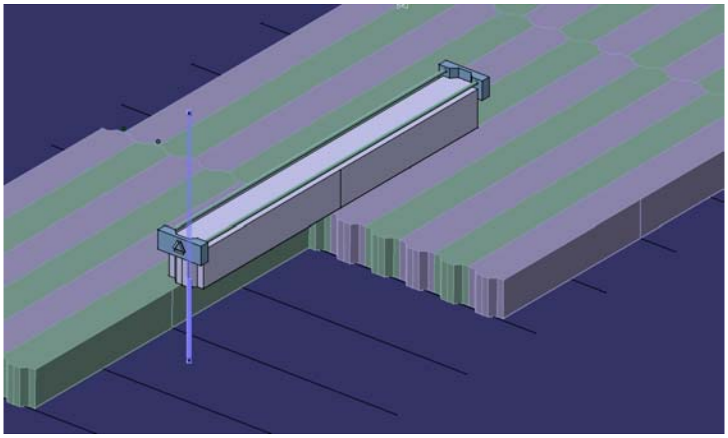


Figure 5.6 Assembled boxcars.

The ends of the cylinder are sealed in any of various ways. Once the shell structure is completed, the radiation shielding for the ends can be accomplished using flexible bags containing water and/or hydrogen – or more boxcars containing regolith. *However, in our costing in Chapter 6, we assumed that the same regolith/ boxcar system was used to seal up the entire side faces, with radial cables for initial support.* There is no need to pressurize and shield regions other than those to be inhabited or cultivated. To create atmospheres, inflatable balloon structures are adequate. Sunlight will be directed in through the endwalls, with appropriate filters. Figure 5.7 is an artist's conception of the completed habitat, with pointable solar arrays shown attached.

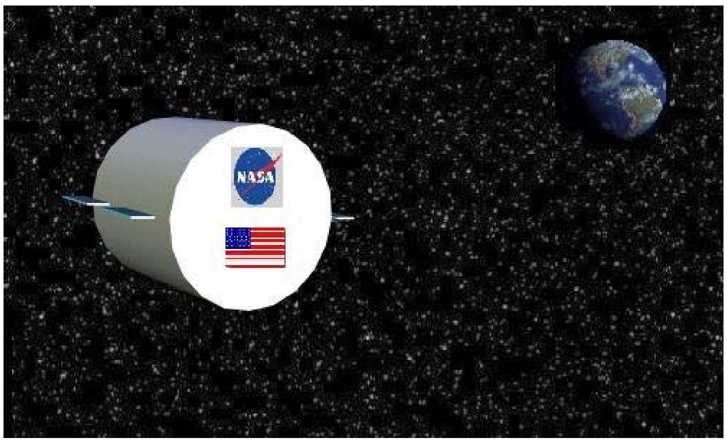


Figure 5.7 Artist's conception of the completed cylindrical habitat.

5.5 Summary of Construction Parameters

Table 5.2: Construction Parameters of 1km cylinder radiation shield:

• Radius = 1km; 0.945 rpm for 1g	• Boxcar dimensions: 2mx2mx 20m
• Length = 2km	• Regolith Mass/ load: 160,000 kg.
• Shield Depth 2m	• 10 launchers operational at any time (20 total around lunar equator)
• Grid current = 35 amps	• Shepherd unit current: 5 amps
• Loops of cable; Wire dia =12.5mm	• Time to build: 10 yrs.
• Solar Panel area to power grid = 350 m^2	

5.6 Summary of Construction Sequence

•Lunar Solar-Power Fields made by robotic rovers around the equator
•Lunar metal extraction; cable manufacture using robotic plants.
•Lunar launcher construction.
•First cable-set deployment and spin-up.
•First ring of loads forms framework for subsequent cables & loads.
•Solar collectors, thrusters; hub with tethers and "Construction Spiders".
•Oxygen / propellant extraction from regolith for thrusters.
•Cylinder completion; endcaps sealed with regolith and water bags;
O2/N2 bubbles for habitation near rim; micro-g axial facilities.
•Human habitation commences.

5.7 Issues requiring further detailing

Shepherd craft - propulsion

Current concepts (e.g. Figure 5.8) for Orbit Transfer Vehicles visualize solar-heated gas-powered vehicles which will perform transfer missions between Low Earth Orbit and Geosynchronous Earth Orbit. This is appropriate for the shepherds; however, it is not possible to have a large solar collector attached to such craft because the shape must enable it to move in the narrow space between the Spider grid and the cables. Focused sunlight beamed from the Moon or the cylinder constitute one option for heating the gas. The gas supply must be replenished either from supplies on the cylinder, or (more likely) from a pressurized cylinder carried with some of the boxcar loads. This will leave a large number of such cylinders to be disposed at the cylinder – or used for storage of gas extracted from the regolith at the cylinder. One option is to use the robot arms on the Spider to refill these cylinders from ISRU units, and attach them to the thrusters needed to replenish the angular momentum of the cylinder.

Figure 5.8 STUS concept. Credits: NASA Marshall Research Center.

Shepherd craft – electromagnetic force.

A set of 3 electromagnets arranged in a "delta" on each end of the shepherd can serve to provide enough maneuvering forces and moments during interaction with the field due to the grid held by the Spider. Superconducting magnets may be an option for this use, with developments in the technology. Power for these magnets could come from beamed power from the cylinder, charging storage units on the shepherd. Coincidentally, when electromagnetic Shepherds were first being proposed to NIAC (Feb. 2001) for this application, LaPointe [34] was also proposing "Shepherd" electromagnetic craft for formation flying.

Optimal orbits and launch sequences.

As discussed above, there has been considerable work done on determining optimal trajectories and launcher locations, but with the O'Neill system architecture in mind. These should be adapted to an architecture which considers solar-power fields and metal mining/extraction sites on the Moon. Other issues related to this architecture are discussed in the next section where the cost of this project is considered.

6. Exploration of cost and architecture models for a Space-Based Economy

6.1 Introduction to the Space-Based Economy Concept

In this section we present an architecture which will lead to an expanding human presence beyond Earth, which will also provide a relevant framework for most of the advanced concepts presented by NIAC innovators.

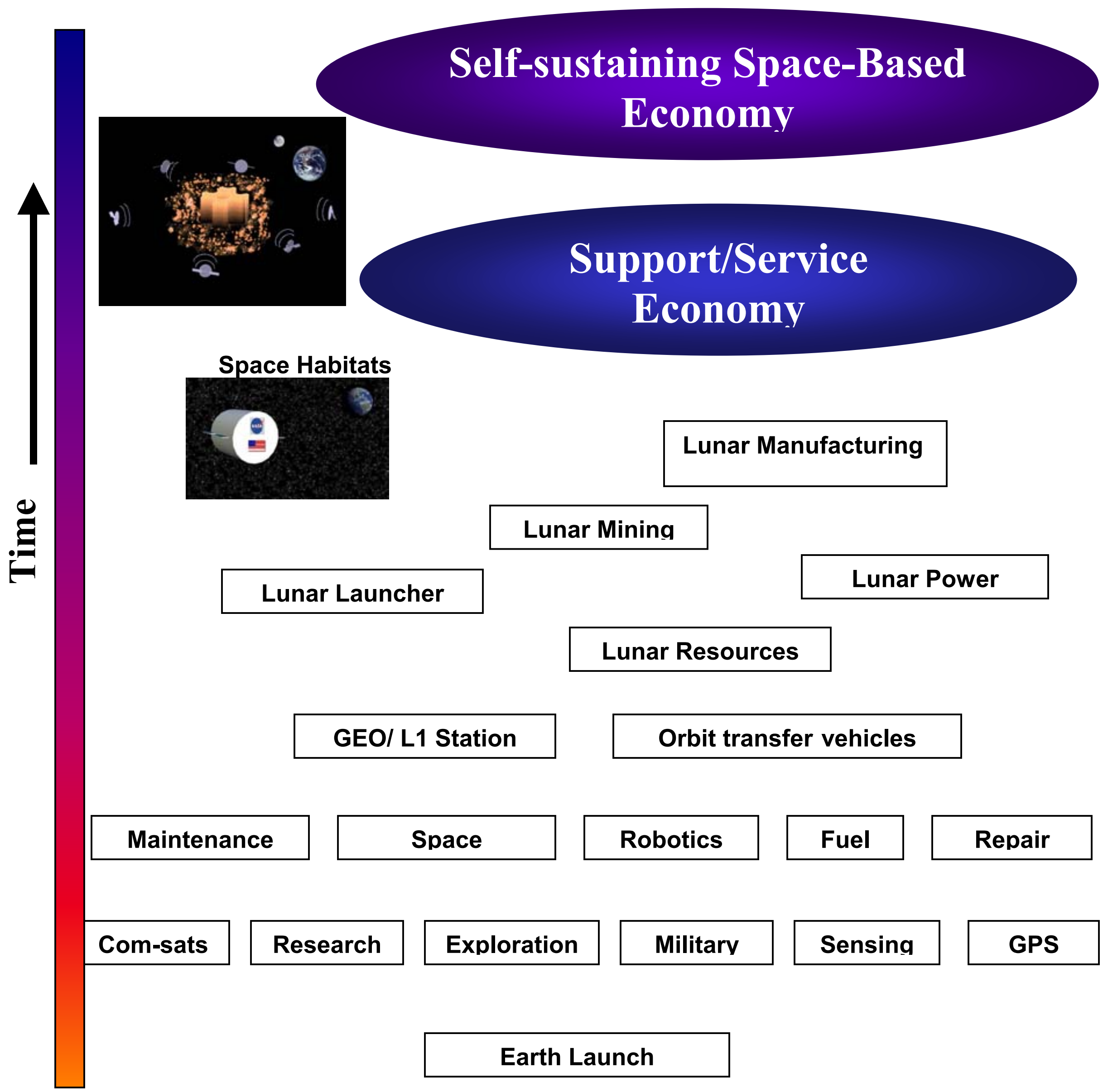


Figure 6.1Evolution of the Space economy

Figure 6.1 considers the evolution of space-related economic enterprise. In the 1950s the primary challenge was to develop launch vehicles and systems to reach outer space. In the 1960s to the present, space-related enterprise has developed with communication satellites, research probes, exploration missions, the remote sensing business, the Global Positioning System, and of course the vast range of military missions to Space. The Mir space station and the International Space Station have developed a rudimentary system of routine missions to Space with semi-permanent occupancy. In the near future, we expect to see a maintenance business developing, with the stated intention of the military to refuel their satellites in order to enable more frequent orbit changes as required to monitor evolving situations anywhere on the globe.

Once a refueling capability develops, many expensive 3rd stage cryogenic engines may become recoverable, and an associated maintenance business will develop. Orbit transfers will thus become more routine and less expensive. Repairing and refurbishing large satellites in GEO will then become economically attractive, with an attendant reduction in the risk and insurance premiums for launches to GEO. The need to build heavy redundancies into large satellites in order to achieve 30-year lifetimes will no longer be essential. With this will come a growing demand for stored spare parts, fuel and materials in orbit, with provisions for saving the fuel left over in launch vehicles, as well as STS main tanks. Thus will develop the need for larger stations at Earth-Moon L-1 or L-5.

At this point, the exploitation of lunar resources, especially oxygen, becomes increasingly attractive. Once a demand for ISRU units for oxygen extraction arises on the Moon, concepts for lunar solar power also should develop. These in time should lead to a growing industrial presence on the Moon. These developments will, in time, lead to a demand for orbital habitats, and then to resource extraction from the Near-Earth Objects, which appear to be promising sources of water ice, carbon and metals. As these enterprises develop, the primary markets, and the primary suppliers, of Space-related business will be located away from Earth – a true Space-based economy. Given that resources accessible on Earth are only a very small fraction of Solar System resources, it is evident that the Space-based economy will surpass Earth's within a relatively short time beyond this stage, and has boundless potential for growth Below, we examine the costs of accelerating much of this development sequence using a synergistic plan to develop the first large habitat. Once this project develops infrastructure, NEO resource extraction would become much more feasible – driving demand to build large habitats in the NEO region.

6.2 Arguments for a Space-Based Economy Approach to Building Habitats

The cost of building a habitat is dominated by that of the radiation shield and outer shell. With our proposed automatic technique, the cost of actually building the shell is made negligible in comparison with that of delivering the huge amount of material to L-2. The operating cost for this delivery is negligible (little recurring fuel cost except for orbit corrections of the Shepherds) compared to that of amortizing the electromagnetic launcher. The key to making such an immense project affordable is to ensure the congruence of various needs for such launchers on the Moon. Prior work on Space Manufacturing looks at manufacturing in space using non-Earth based resources and energy [35-38]. The Report of the National Commission on Space, 1986, [39, 40] emphasizes an economical, phased approach for space exploitation, which will be technically reasonable, and will support private enterprise. It focuses on the benefits that can accrue to humanity and the nation in particular. The report, however, stops short of outlining a clear vision of the concept that will integrate Science, Technology and Economics. That concept is the Space based Economy.

6.3 Snapshot of Today's Space Economy

The human presence beyond Earth today is limited to a very few dedicated government employees and robots who are dependent on Earth-launch of all resources except sunlight. The only permanent facility beyond Earth is the ISS, whose total living space is comparable to that of a classroom. While commercial spending on Space, worldwide, surpassed government spending as of 1997 [41], and the satellite business generated over $81B in revenue [42] in 2000, the Space industry and the exploration/ utilization programs cannot be described as being "healthy". What Scientific American saw as the "Gold Rush into Low Earth Orbit" [43] in 1999 has stalled, with most launch system startups reported to be in trouble. NASA's X-30, X-33 and X-34 programs stand canceled. The Mars program has seen a dramatic drop in ambition level from "Permanent bases by 2018" in 1985, to "robotic exploration missions to Mars Orbit until 2020" in 2001 [44]. Cost "growths" [45] on the ISS have forced NASA to cut into even these modest plans in 2001. In an environment of declining public interest and funding, the scientific debate about

Space priorities pits proponents of various approaches in conflicting positions, perhaps destroying support for all missions.

6.4 Differences in Proposed Approach

It is appropriate to ask: *"What can be done differently to improve the rate of progress?"* The literature on Space Commerce has focused on transportation, communication, remote sensing, and, to some extent, manufacturing. "Infrastructure" has usually been taken to mean Earth-based infrastructure [46-49]. Table 6.1 summarizes the differences in concept between today's Space economy, and a true Space-Based Economy (SBE). The SBE provides a vision which unifies proponents of robotic exploration, human exploration, lunar resource utilization, and asteroidal resource utilization – who today compete, often destructively, for a diminishing pool of public support and funding. The SBE vision follows a 'policy resilient approach', which builds up infrastructure to support multiple uses and goals.

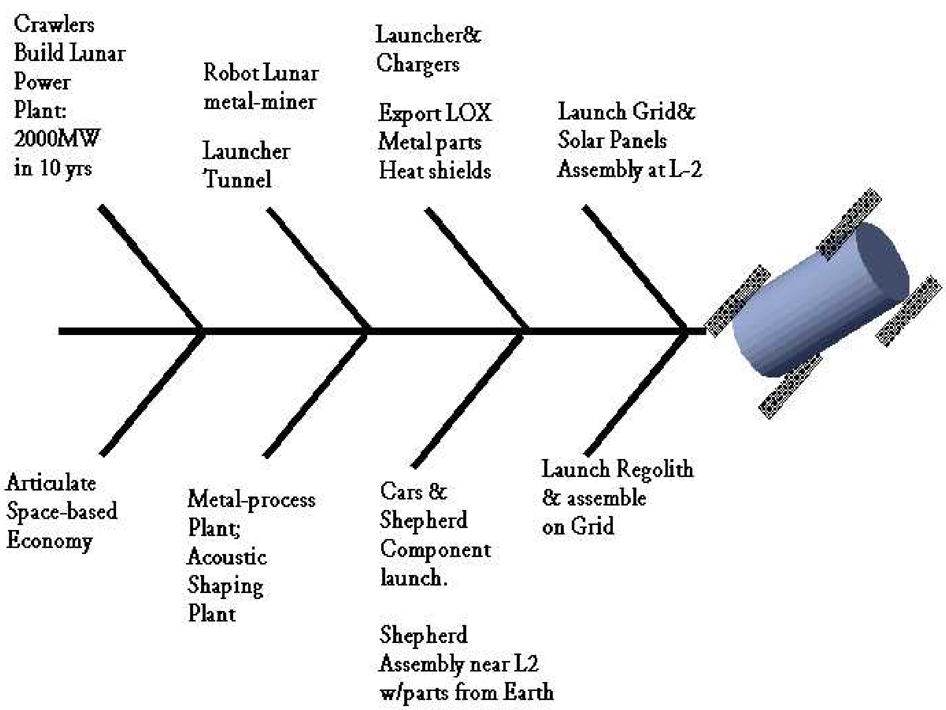


Figure 6.2: Synergistic Architecture for the Habitat Project.

Table 6.1: Differences Between Today's Space Enterprise and a Space-Based Economy

Current models of Space Enterprise	Space-Based Economy
• Earth as the only possible market. • "Faster-better-cheaper" to compete in today's global business environment. • Three-to-five year Return on Investment (ROI) expectation by investors. • Terrestrial launch cost reduction as key enabler. • Lack of infrastructure for repair or resupply sharply heightens risk for all investors. • Support constituency: NASA Centers, Space launch companies, space science community • Competition for decreasing government funds forces adversarial competition between segments of the Space-enthusiast community • Limited and decreasing interest and funding	• Most raw materials and products originate outside Earth • Large Space-based infrastructure • Extra-terrestrial raw materials extraction and processing, • Large scale manufacturing capabilities in space, • Exchange of products and services between space-based enterprises. • Support constituency: diverse businesses and professions – broad cross-section of taxpaying public • Required critical mass of funding and long-term investment rules out private funding.

6.5 Educating the Public

The concept of a Space based Economy can bring various businesses together. The business plan of a single industry that may appear risky and unsubstantiated when viewed by itself, can become realistic when patched into the network of a Space based Economy. From discussions with various graduate classes on Strategic Marketing, we conclude that the key to attracting public interest is the provision of clear knowledge and methods to reduce risks and calculate business models. This process involves technical, economic and political aspects which we summarize below. A detailed form of the Fishbone diagram shown in Fig. 6.2 can be used to develop every step needed for the SBE project. Technical risk can be reduced, and calculated, by developing alternative markets/ uses for all the technologies which require large investment in the process. Such a process will also clarify and allow articulation of the relevance of the SBE to all segments of society. The availability of knowledge on what has been tried before, and on all the studies which have been performed, is a vital step towards such risk-reduction, and is being undertaken at Georgia Tech's Center for a Space-Based Economy (CSBE).

Table 6.2: Steps in Articulating a Space-Based Economy

Setting up a space based Economy:	Key Requirements
• Give businesses a vision of the new markets to be explored and exploited in space. • Bring together authorities from the Space Resource Utilization, tourism, construction, aerospace, and other businesses with visionaries on space exploration to work towards realizing this goal of a Space-Based economy. • Outline key requirements needed to establish a space-based economy. • Give examples of potential space business ventures to demonstrate feasibility of space-based businesses and benefits to exploration plans. • Educate people about benefits to standard of living. • Inform lawmakers of the prospects of improved tax base, and economic development of the nation as a whole.	• *A clear vision of a Space-based economy, showing how most people and industries can consider themselves to be stakeholders in this endeavor.* • *Belief that such a space-based economy will develop* • *A credible plan on which to base this belief* • *Concrete examples of ventures in space, and predicted returns to attract industry interest.* • *Project planning, cost estimation and risk-reduction strategies to articulate the definite steps towards the space-based economy* • Communication of mutual interests between NASA, business, industry and lawmakers.

6.6 Cost Estimation Approaches

Several levels of estimation can be considered. An upper bound is obtained by the 'Delivered Cost Approach' [50] where the cost of materials delivered at a given point in Space would be limited (a) from above by the cost of getting similar materials delivered from Earth and (b) from below by the supplier demanding the most that the market will bear. This approach will result in few projects being feasible. Secondly, one can estimate the capital cost of constructing the entire Space-Based Economy. A third approach is to bring in all players at the outset, and figure the costs and risks to each, given the presence of the rest. Ignatiev [51] estimates a robotic 10,000 MW solar power plant on the Moon at $ 62B in year-2000 dollars. This will have a multi-customer base, including mining, fuel extraction, manufacturing and launch services. The cost for strip mining on the Moon is estimated as $3 B in year 1979 dollars [52], extrapolated using Consumer Price Index Inflation to $ 8B in 2000$. For the Lunar Launcher System, the cost in 1977 dollars, adjusted for inflation, gives a Present Value estimate of $8B.

As more businesses are enabled by the "assured market" of the Radiation Shied project, the required public funding drops. The requirement drops from $200B if the Shield is the only end-product, to $130B if it buys power from the lunar power plant while assuring the power-producers of demand during the initial decades of their production. With power, and materials available, the launcher cost comes down, again with an assured and diversified market to reduce risks in its development.

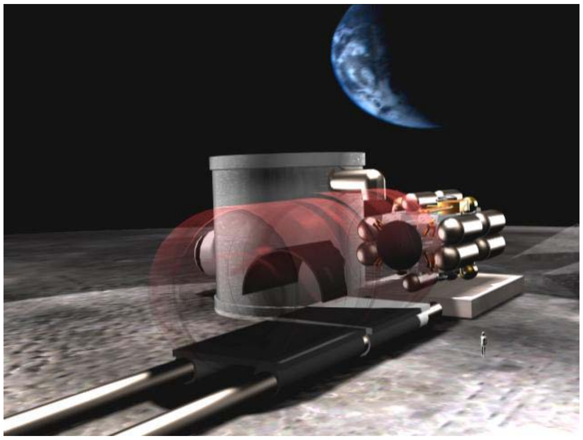


Figure 6.3: Artist's Conception of an Acoustic Shaping Plant on the Moon. Courtesy, Justin Hausamann, Georgia Institute of Technology, School of Aerospace Engineering, 2000.

6.7 Summary of Industry & Infrastructure Bootstrapped by Habitat Project

The following extraterrestrial industries and infrastructure will be enabled in a synergistic Habitat project through the architecture which is described above. Each is provided with an assured market, both from the habitat project, and from the other projects enabled.

- Power plant.
- Metal mining.
- Flexible manufacturing facilities for cables, metal panels, box cars, rails.
- LEO – GEO – Lunar Orbit shipping industry
- Tether system for delivery to the Moon.
- Electromagnetic rail launchers – nucleus of circumlunar ground transport system.
- Oxygen extraction plants on the Cylinder and the Moon
- Solar panel production
- Repair, exploration and prospecting facilities on the Moon.
- Habitat sized for eventual population of 10,000 people in orbit.
- Means to ship construction materials anywhere in the vicinity of Earth

6.8 Total market for lunar resources due to the Habitat Project
The total markets for lunar resources, enables by the Habitat project, are summarized below. Details are given in the next section

•Steel 2.8 million tons over 11 years
•Or Ti: 1.5 million tons over 11 years
•Regolith: 75 billion tons over 11 years
•Power: 66,200 GWh just for launch services; plus power for manufacturing.
•Manufacturing: 470,000+ boxcars; 960 km of e-mag rails.

Notes:
1.The Radiation shield of 2m regolith is extremely conservative, and used only for illustration of very large-scale mass transport. Concepts for lunar hotel radiation shields use 0.4m of water.
2.Professors Ignatiev and Criswell now estimate that beyond an installed capacity of 1GW, their solar-powered lunar power plants could generate electricity at a marginal cost below $0.01. We have not included this drop in our cost estimation.

6.9 Architecture of the Space City Project:

It is a considerable challenge to argue in favor of the financial viability of Long term Space Projects, with their high risks and long gestation periods. It is vital to develop a coherent plan for the organization, which outlines the Architecture of the Project. The Space Based Economy (SBE) concept helps in bringing together different technologies and enables them to reduce risks. This generic Architecture lays out a roadmap for SBE stakeholders in formulating plans that fit into the domain of the SBE.

6.10 Cost Model for the Space based Economy

In developing a cost and risk model for the project, we consider the implications of synergizing these technologies, with each providing assured markets / supplies / raw materials for others. Alternative technologies are considered for each major component of the project. The risks associated with the project are mitigated by laying out alternative products and intermediate markets for each major technology developed for the project.

The Cost Model for the Space based Economy (SBE)™ follows a Cost-Technology Matrix Approach (C-TMA)™. The matrix factors both the risks of technologies available and the market elasticity, in order to select from among the various technologies available in the SBE. This means that we not only weigh the various technologies available for a particular process quantitatively on the basis of cost, but also rank them qualitatively by risk-rating against Technology, Ecology and Political Environment. The technologies available are worked out based on expert group opinions and literature search. The risks of technical obsolescence, scalability and sustainability are weighed into the technological availability by using a weighted questionnaire that ranks individual technologies. However, the unique aspect of a C-TMA is that the market elasticity of the chosen technology is taken into account. This is ideally done with the help of an Expert Group that assesses future markets for each technology using analogies, group discussions and extrapolation based on historic data. It is not possible to accurately forecast market demand for nascent technologies many years into the future. Also, prediction of a fixed market size could lead to errors in project planning. Thus the focus was on defining a credible range of future alternative users and assessing the demand elasticity for these technologies.

The most suitable technology is chosen by comparing the alternatives in the Cost-Technology Matrix (C-TM)™ against quantitative cost and qualitative risk terms. Once the most suitable technology is chosen and the Cost-Profit-Demand-Elasticity calculated, the Cost calculation of the Space City project can be done. The point to note is that the SBE not only helps the Space City project to choose among the various technologies, but also helps the Technology provider to know the Cost-Profit-Demand elasticity required to attract Capital funding. The SBE is the synergistic fulcrum that brings together the Technology providers into a common working space. The Cost Constants can be refined with the help of Expert Group analysis, extrapolation of earlier studies and analogies. The main Cost Drivers are identified as shown in Table 6.3. The cost analysis is also set up so that the elasticity of cost to these price constants could be calculated to find out the most probable cost as per Expert Group assessment. The final Cost assessment is given in Table 6.4.

Table 6.3 Cost-Drivers for the Cylindrical Habitat Project

Item	Sub-item	Cost in US$ (2002)	Units	References
Material Costs:	Cost of Steel on Earth	5	per kg	Present Cost
	Cost of Aluminum on Earth	3	per kg	Present Cost
	Cost of Iron on Earth	1	per kg	Present Cost
	Cost of Steel on Moon	12.5	per kg	Expert Group
	Cost of Aluminum on Moon	12.5	per kg	Expert Group
	Cost of Iron on Moon	12.5	per kg	Expert Group
	Cost of Concrete on Moon	5	per kg	Expert Group
	Cost of Shepherd fuel on Moon	10	per kg	Expert Group
	Cost of Regolith on Moon	0.06	per kg	Ref: Excavation costs for lunar materials, David Carrier
Launch Costs	Cost of Launch from Earth to L2	4000	per kg	Expert Group
	Cost of Launch from Earth to Moon	5000	per kg	Expert Group
Power Costs	Cost of Power on Moon	0.4	per KWH	Ignatiev et al [51]
	Cost of Solar panels at L2	50000	per sq m	Expert Group

Table 6.4 Final Cost Analysis for the Cylindrical Habitat Project

in US BN $ (2002)

Year	Process	Material Cost	Earth Launch cost	Launch Power Cost	Power-L2 cost	Fuel cost	Total
1 & 2	Mass Driver Construction	6.5	0.0	0.0	0.0	0.0	**6.5**
	Winch	0.0	0.0	0.0	0.0	0.0	**0.0**
	Shepherds	0.0	0.0	1.0	0.0	31.8	**32.8**
	Crawlers	0.0	0.0	0.0	0.0	0.0	**0.0**
3	Wire Grid	0.0	0.0	0.0	0.0	0.0	**0.0**
4 to 13	Boxcars	66.0	0.0	25.5	0.0	0.0	**91.5**
	Spin-up city	0.0	0.0	0.0	0.0	0.0	**0.0**
	Total	**72.5**	**0.1**	**26.5**	**0.0**	**31.8**	**130.8**

Power Requirements: We assume an installed capacity of the Ignatiev Power plant of 1,000 MW, distributed around the lunar equator. The cost is assumed to be $ 0.40 per kWH. Table 6.5 considers the launch requirements. From the table, we can see that the rated power capacity of the power plant is capable of supporting 6 launches an hour, with an excess of 18% for other uses, which amounts to 188,000 kW-h every hour.

Table 6.5 Power requirements

Ignatiev power production: 1GW capacity

	3.6E+12	joules/hr	
	1,000,000	kW-H- every hour	
6 launches/hr requires	811,988	kW-H- every hour	
Excess power available	188,012	kW-H- every hour	18.80119907 %

Excess Launch Capabilities: The exact requirement of the number of launchers for construction period of 10 years is 5.6 launchers. Since 6 launchers will be built, this gives a considerable excess launch capacity, which can be used for other applications. The details are shown in Table 6.6

Table 6.6 Launches available for other economic uses

Launches for other uses

Time required for launch of all boxes with 6 launchers:	9.307311091	years
Time available for other launches	0.692688909	years
Extra boxes that can be launched	36408	boxes
Extra mass launch capability	**6,104,271,627**	**kgs**

can be used for other application launches

6.11 Technology Options

In this section, we lay out the conceptual process for reducing the risk and cost of the cylindrical habitat architecture. For each aspect, there are different competing technologies, of which one is taken as the preferred option, with alternatives which might become the preferred option if political or other technical developments so dictate.

Power

Preferred Option:	**Alternatives:**
• Lunar Solar-Power Fields made by robotic rovers. - 20 power plants around the equator • Cost estimate: $0.40 per kilowatt-hr (Ignatiev et al)	• Nuclear Power Plant on the Moon • Beamed Power from Space Solar Power Plant

Metal Mining & Extraction

Preferred Option:	**Alternatives:**
• Lunar open-pit mines for iron (est: 4 – 15% of lunar soil is Fe, occurring mostly as oxides). • Solar-heated metal extraction processes – vapor separation more viable than chemical reduction? • Robotic fabrication plant shipped to the Moon for box-cars, launcher rails, structural cables, conductors and magnets for launcher	• Pre-fab delivery from Earth using tethers. • *Steel production on Mars, delivery to Moon.* • *Start with earth-delivered boxcars to build initial structure; Ship Fabrication plant to cylinder site; ship steel rods from Mars to cylinder site; land boxcars on Moon and re-use;* • *Asteroid resources.*

Launchers from the Moon

Preferred Option:	**Alternatives:**
Electromagnetic rail launcher sized to launch boxcar-sized loads at 8G, with carriage returning to starting point. Some power is re-cycled during the deceleration leg. •Power from local plants. •6 launchers placed around lunar Equator to enable round-the clock operation. 80-90% of power plant capacity utilized by Cylinder project for 10 years; • Rest used for export of oxygen & tether counter-masses •Tethers and launchers form transportation system for industrial development on the Moon.	Tethers (problem: counterweight mass; repetition rate needed) •Nuclear rockets (need propellant gas)

6.12 Concluding Remarks on the Space-Based Economy Approach to Building Habitats

This chapter takes an initial look at the requirements for setting up a Space-Based Economy. The technical issues in building the massive radiation shield for a human settlement, are reviewed in the light of today's capabilities for robotics and communication. By including the visions of several concepts such as lunar-based power, mass drivers and resource extraction, it is shown that the overall cost of such a major project can be brought down to imaginable levels. As more business visions are enabled by the assurance of a massive market provided by the infrastructure project, the level of public funding needed for the infrastructure comes down, even before tax revenues begin. The process for gathering public support for such an Economy is considered. Unlike today's exploration-focused government Space program, and isolated business plans for private ventures, the SBE can unite the public in supporting the Space enterprise.

The relevance of this discussion to the present NIAC project is that it lays out the process for enabling the grand developments which develop demand for extraterrestrial resources. This demand in turn sets the scene for the development of habitats to exploit resources from the Near Earth Object region, Mars, and beyond.

7. Task Report: Exploration of large-scale construction using Radio Waves

7.1 Introduction

In Chapter 3, we have shown that the theory for radiation force in beams and standing-wave fields is essentially the same in electromagnetic fields as it is in acoustic fields. Thus, we postulate that complex shapes of stable "trap" surfaces can be generated in electromagnetic fields as well. The calculations in section 3 provide a simple basis for estimating the power required to accelerate particles of given size using radiation of given wavelength, as long as the scattering is still in the Rayleigh regime (particle diameter less than 10% of wavelength). The choice of the Rayleigh regime is made to simplify the calculations. If the radiation wavelength is reduced for a given particle size, the acceleration per unit intensity is higher, but it is harder to predict, and perhaps to control. With advancements in prediction capability, it should be possible to take advantage of the Mie regime where the wavelength is the same order of magnitude as the particle diameter.

7.2 Radio Wave Tailored Force Fields

Small asteroids in the Near-Earth Object region in Earth's orbit around the Sun may be used as the source of raw materials for building large, radiation-shielded habitats. The NEO region is chosen because this is the most likely region for the first large-scale resource exploitation efforts of humanity, beyond the Moon. The L-5 region of the Earth-Sun system is believed to have entrained thousands of objects which are either asteroid fragments or cometary fragments. Some are believed to contain water ice and carbon, while others may have substantial metallic resources. Suitable construction material for our purposes would be metal oxides such as silicon dioxide. The signal round-trip time from Earth is on the order of 20 minutes; the diversity of resources in the region demand intelligent presence. For these reasons, this region is most likely to have the greatest need for a permanent, large, radiation-shielded habitat.

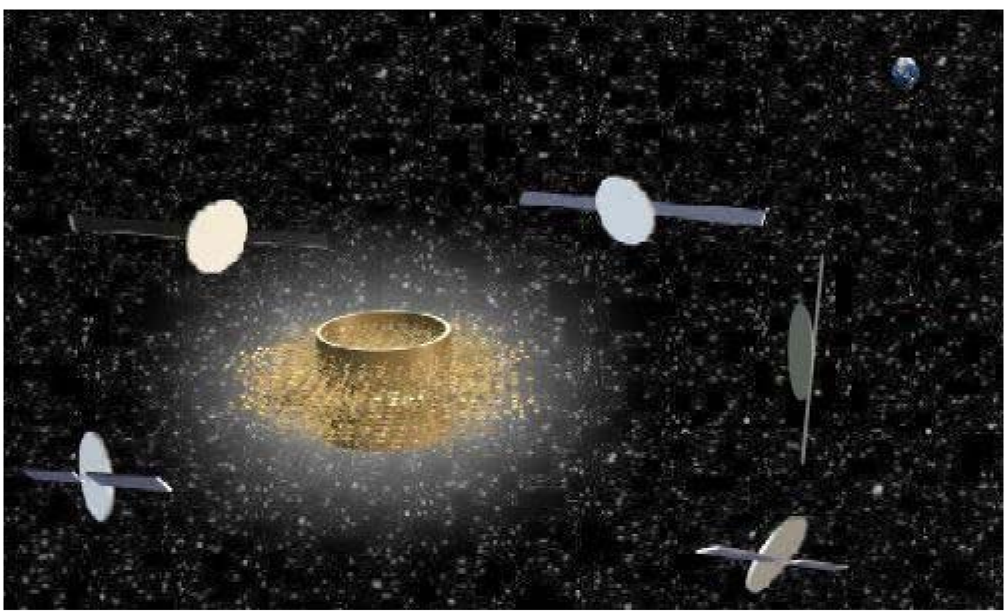


Figure 7.1 Conceptual drawing of a large radiation-shield being formed using radio waves, from pulverized asteroidal material. Earth is shown much larger than it would be seen from the Near-Earth Object region at the Earth-Sun L-5

A conceptual drawing is shown in Fig. 7.1. Magnetic fields separate different materials. Electromagnetic fields move the desired materials near the nodal planes of the resonator, which depend on the driving frequency. The material forms walls along and parallel to the nodal planes. Energy at other frequencies is beamed to melt and fuse the walls; radiant cooling hardens them into rigid structures. Radiation-shielded habitats could be formed for the first resource-prospectors and extraction crews to live in this region. Spaceship structures could be formed for long-duration missions.

For a single-point design example, we assume that the basic construction material to build a radiation shield will be blocks roughly 0.2m in diameter, obtained by breaking pieces off asteroids. The appropriate radiation for this would be radio waves in the 2MHz to 5MHz range. In this regime, high-power transmitters can be built, with excellent conversion efficiency from solar-generated electricity.

7.3 Calculation of Radio Wave Intensity and Solar Energy Requirements.

The estimation technique developed in Section 3 is used below to obtain the acceleration per unit radiation intensity for a particle inside a resonator, with the particle radius being 5% of wavelength in order to keep the calculation in the Rayleigh regime. In this regime, the shape of the particle is not significant, and hence an effective radius is used as a characteristic dimension. The results are shown in Table 7.1. Clearly, a very high intensity of radio waves will be required to cause any significant acceleration. This is why the first applications of this technique will probably be in a region of vacuum where g-jitter and other acceleration errors will be minimal.

Table 7.1 Estimate of acceleration per unit intensity for radio wave TFF

Refractive index of the particles n1	1.51
Refractive Index of medium (vacuum) n2	1
Particle material density, kg/m^3	2000
m = n1 / n2	1.51
Ratio of wavelength to particle effective radius (assumed to stay inside Rayleigh domain)	1000
Effective Particle radius a (m)	0.1
Wavelength (m)	100
Acceleration per unit intensity (SI units)	2.99E-14

An example of the power needed is given below. To form a cylinder 50 m in diameter and 50 m long we would excite a 220 mode in a rectangular cavity of dimension comparable to 50 x 100 x 100 m. In the below power calculation a radio beam 100 meters in diameter was conservatively used for comparisons with conventional data. The choice of habitat dimension in this case is argued as follows: Unlike the 1km-radius cylinder considered in Section 5, this one is intended for sparse inhabitation, primarily by technical people, and primarily for shelter in the NEO region. It is not intended as a permanent habitat. The present conception of the construction method envisages a resonator set up using large moveable antenna arrays – thus the size of the structure built in one formation operation, will be limited by the resonator size. It is also likely that these structures, once assembled, may have to be propelled to different regions. In this case, it is more practical to build the shelter in modules, then attach them using tethers and set them in a 1-rpm revolution with a 1km radius, in order to obtain 1-G. These considerations justify the selection of a 50m diameter by 50m long cylinder as the initial test case. The results are shown in Table 7.2.

Table 7.2 Parameters for building 50m long cylinder at the NEO site at the Earth-Sun L-5 region

Solar intensity at site orbit, w / m^2	1380
Particle Effective Radius for construction: (m)	0.1
Wavelength (m)	100
Acceleration per unit intensity	1.50E-12
Acceleration selected, m/s^2	9.81E-06
Intensity needed, w/m^2	3.28E+08
Size of object in beam, m	50
Beam dia, m	100

These results are translated to radio wave and solar power requirements in Table 7.3. The choice of beam diameter with respect to object size is arbitrary – there must be a criterion which can be used to optimize resonator size and Q-factor in this regard. This is an issue for further study in Phase 2.

Table 7.3 Radio-Frequency Power and Solar Power Requirements

Power required, w	2.58E+12
Resonator Q factor	10000
Power input needed, w	2.58E+08
Solar converter efficiency (10%)	0.1
Solar collector area, m^2	1866770
Collector side, km	1.3663
Collector materials and mass per unit area	6
Collector mass, kg	11200620.6
Time needed to assemble structure, hours	6.27
Total energy needed (kWh)	1.62E+06
Structure total mass, kg	12,96,640

The collector mass is calculated, assuming a nominal panel thickness made of lunar regolith-derived material. Thin-film solar collectors may be an option, but the manufacture cost must be traded off against the shipping cost – an issue for Phase 2. The assembled structure itself is assumed to be a 2m thick cylinder. The particle acceleration level is chosen to be well above the acceleration level due to any background radiation. With the level chosen above, particles will drift into position within about 1 hour. The total of 13 hours is chosen to provide enough time to fuse critical portions of the structure in place (using focused beams not considered in the above power calculation), so that the rest of the structure can be completed after the field is turned off.

7.4 Magnitudes of other accelerations expected in the NEO region

Magnitudes of other accelerations are estimated in Table 7.4 and the following discussion. It is easily seen that an acceleration of 10^{-6} G's is adequate to overcome the worst of these.

Table 7.4 Data for solar effects on particle acceleration

Mechanism and effect	Basis for calculation
Solar Gravitational Attraction Balanced out in orbit around the Sun; jitter time scales are >> time scale for assembly of an object using TFF; jitter amplitude negligible.	$g = \frac{-Gm_{sun}}{r^2} = 0.00593 \frac{m}{\sec^2}$ Where r is the distance from the Sun (1 AU = 1.496E+11 m)
Solar Wind: Proton Density varies from 0.4 to 80*10^6 per m^3 and velocity ranges from 300 to over 700 km/sec at Earth orbit ; particle of 0.1 m^2 and a density of 2000 kg/m^3 was used in these calculations. Acceleration = **6.2722E-11 m/s^2**	Refs: Zeilik, Michael and Stephen A. Gregory. *Introductory Astronomy & Astrophysics*. Brooks/Cole Thomson Learning, 4th Edition. Took an average so used 40.0E6 and 500,000 m/sec respectively from above. Mass of proton is 1.6726231E -27 kg $A \times V = \pi \times r_{particle}^{2} \times V_{solarwind} \times \rho_{solarwind}$
Radiation: Use the fullequation from Zeilik, gives: **1.7361E-8 m/sec^2.** Note: the assumed solar intensity value of 1380 watts/m2 gives **1.755E-8m/s^2**	$a_R = \frac{\left(\frac{\pi\sigma r_{particle}^{2} R_{sun}^{2} T_{sun}^{4}}{c}\right)}{d^2} / m_{particle}$ Where σ is the Stefan-Boltzmann Constant = 5.6705×10^{-8} W / ($m^2 K^4$) $\pi * r^2$ is the area of the particle $R_{sun} = 6.9599 \times 10^8$ m = Radius of the Sun T_{sun} = 5800 K = Temperature of Sun 'c' is speed of light 'd' is distance from the sun (1 AU in this case)

The gravitational acceleration on the particles due to the rest of the particles in the "construction zone" is estimated as follows. The worst-case is the acceleration on the last 10-cm diameter construction particle due to all the rest. Assume that the largest single manufactured component is a hollow cylinder 50 m in diameter, 50 m long, with a wall thickness of 2 m, made of silicon dioxide, with a density of 2000 kg/m^3 Figure 7.2 illustrates the worst-case situation where all construction material is agglomerated into a sphere, and the last particle is right at the surface of this sphere.

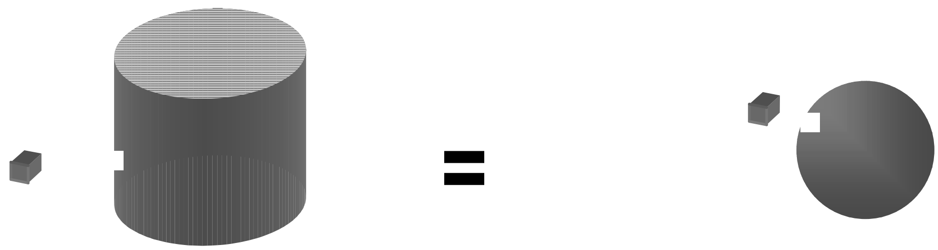


Figure 7.2 Worst-case model for gravitational acceleration on particles in the construction field.

Volume = 15079.7 m^3, therefore mass of cylinder, or sphere = 3E7 kg
Therefore, radius of equivalent mass sphere = 15.3 m
Gravitational force at surface **= 8.6E-6 m/s^2**

This is still below the 1.0E-6 g's selected. When the particle cloud is formed, some effort should be put into clearing the central region, so that the gravitational acceleration becomes a helpful feature in forming the cylinder, bringing material to the wall of the cylinder.

7.5 Time to Form Structure: a more refined calculation

In the tables above, a first-order estimate was made of the time to form the structure, considering a uniform acceleration on all particles. Below, this calculation is refined using the radiation force in a resonator, using the methods given in [13]. The time taken for particles in all parts of the standing wave field to drift to the cylinder location in a 2,2,0 mode was computed. The following assumptions were made:

Particle diameter: 20 cm (= 2a)

Refractive index: 1.52 (= n1)

Cavity Mode: (2 2 0)

Spacing between source and reflective boundary: 100 m

Structure to be formed: Cylinder 50m in diameter and 50m in height

Wavelength of field, λ: 100m → Radio range

As seen in Figure 7.3, the time taken is well under 1 hour for currently available power sources (MW range).

$n1 := 1.51 \qquad n2 := 1$

$m := \frac{n1}{n2}$

$a := 0.05$ individual particle radius

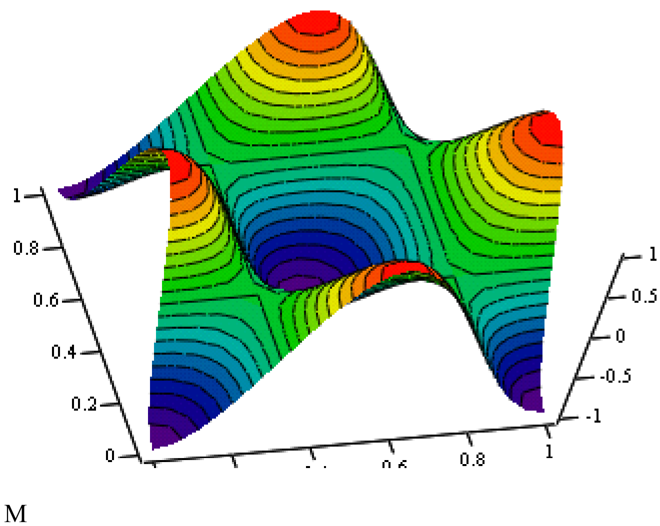
$\lambda := 1000 \cdot a$ wavelength (Rayleigh)

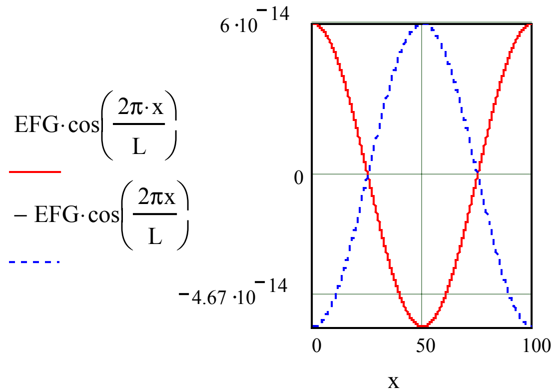
$k := \frac{2\pi}{\lambda}$ wavenumber

$$EFG := \frac{4 \cdot k \cdot n2}{300000000} \cdot \left(\frac{1}{2000 \cdot \frac{4}{3} \cdot \pi} \right) \cdot \left(\frac{m^2 - 1}{m^2 + 2} \right)$$

$L := 100$

$M(t, y) := (-\cos(2 \cdot \pi \cdot t)) \cdot \cos(2 \cdot \pi \cdot y)$

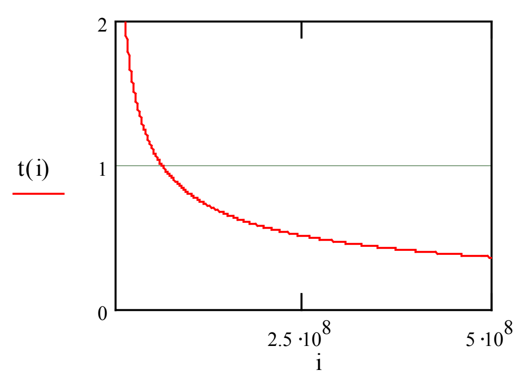




(2 2 n) mode

$$t(i) := \frac{1}{3600} \sqrt{\frac{2 \cdot \frac{L}{4}}{EFG\, i}}$$

assuming zero initial velocity



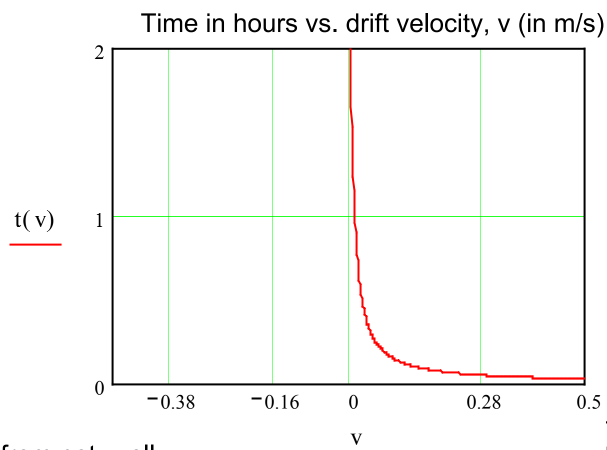
time in hours

Figure 7.3: Calculations for the time taken to form cylindrical walls inside an electromagnetic resonator operated at the 220 mode. (produced in Mathcad). The last curve shows the time taken (in hours) as a function of source intensity. Note conservative estimates were used for sources of radio intensity – above range is from 5MW to 500MW sources.

Including drift velocity of particles before the radiation field is impressed on them:

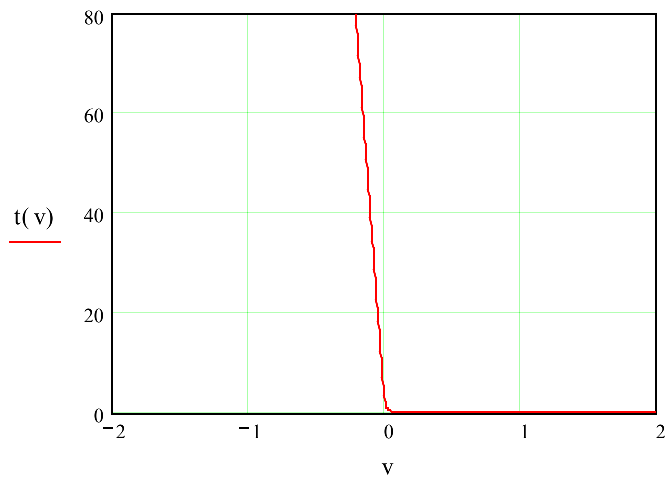
$i := 50000000$ 50 MW source (compare with previous figure - midvalue for source powe

$$t(v) := \frac{1}{3600} \frac{\left(-v + \sqrt{v^2 + 2 \cdot EFG \cdot i \cdot \frac{L}{4}}\right)}{\frac{EFG}{2} \cdot i}$$



-ve v,
away from pot. well

+ve v,
towards pot. well



zoomed out

7.6 Tradeoffs

In the above calculation of radio power, the resonator Q can be traded directly against solar collector area, or a storage system can be developed so that the solar energy can be collected over several months and an intense field can be generated with a low Q-factor. There are at least 3 different design approaches to this, with different technology needs and emphases. One of them is illustrated in Table 7.5 – the energy is collected and stored for discharge during the few hours of construction operations. In this case, the collector area required is quite small. The different approaches to the design of the TFF system are summarized in Table 7.6

Table 7.5: Scenario 2: Collect & store solar energy for discharge during construction, one project per six months.

Energy collection time (months)	6
Collector area for 1.67million kWh, m^2	2735.682
square kilometers	0.002736
Collector side required, km	0.0523

Table 7.6: Technology needs for different approaches to designing radio-wave TFF system

	. High Resonator Q	Medium Q, storage	Low-Q, large collector
Resonator Q	10,000	1000	100
Solar cell area, sq. km	1	1	100
Storage amplifier system	none	Collect for 130 hours, exhaust in 13 hours	none
Antenna technology level	V. high	High	moderate
Solar collector technology level	low	moderate	high
Transport cost	low	moderate	high

From the above numbers, the concept of using solar-powered radio waves to perform such large-scale construction appears to be quite feasible, provided there are markets and infrastructure elsewhere in orbit to provide the transportation and resource exploitation support. The above calculations are no doubt simplistic in terms of the final configuration needed in the future to perform such projects. Several issues for further work are discussed below.

7.7 Antenna / Generator Technology

There has been at least one demonstration that such radio power levels are possible: The Arecibo Transmission. In 1974, the Arecibo observatory transmitted a message into outer space, as part of the Search for Extraterrestrial Intelligence (SETI) program. The power of the transmission was 20 TW. The frequency was 2380 MHz – the wavelength was roughly 12.6 cm. The signal duration was 169 seconds. This power level is well above that projected in the previous pages. Certainly, the hurdles of constructing such a transmitter at the Earth-Sun L-5 region will be a challenge, but it is well within feasibility. The Arecibo facility is shown in Figure 7.4. Issues in the design of antennae/ resonators/ amplifiers for Radio Wave TFF are summarized in Table 7.7

Figure 7.4 Arecibo Space Radio Telescope, Puerto Rico. Credits: Courtesy of the NAIC - Arecibo Observatory, a facility of the NSF. David Parker / Science Photo Library

Table 7.7 Issues in antenna/ resonator design for Space-based Radio TFF

Antenna theory & design considerations; Directivity / Beam Divergence; Gain	Receiver Area Required Power and material requirements	Parameter space and design point
Receiver Materials, Fabrication Technologies, Mass, Positioning, Modes, Converter Area & Efficiency	Solar Collectors as Resonator Walls? Q-factors	Technology status References

The realization that such tailored force fields are indeed within practical conception is new. Further work involving experts in antenna design is needed to brainstorm the implications of this finding, and develop architectures for exploiting this finding, in Phase 2.

7.8 Breaking up the asteroids

In recent years, probes to a comet and an asteroid have successfully completed their missions. Sample extraction techniques involving projectiles have been demonstrated. One of the issues with doing work on an asteroid surface is the difficulty of attaching the craft to the surface – the low gravity level defeats concepts where vehicle weight is used as the counter-balance to exert intense continuous or impact pressure at points on the surface. Future vehicles for such missions will be robotic. The legs may have to drill and thread holes into the surface in order to obtain a firm purchase on the surface. The vehicle may carry a mechanical hammer or a core-drilling machine, operated by solar energy, to break the rocky material into 10-cm sized blocks. If a suitable asteroid is found which is just a loose collection of rocks, the problem reduces to sorting out the bigger blocks to break up.

7.9 Wall thickness and mode-switching

In the acoustic resonator, walls form single-particle thick. What happens when the nodal troughs are filled is not known. Ground experiments show the initiation of several smaller walls parallel to the primary nodal surfaces. If the walls formed reflect the waves in the field, the resonator switches to the next harmonic (that becomes the mode where losses are least). However, if the walls are transparent, then it should be possible to accumulate thicker walls. A more troubling possibility is that the particles may simply slide along the nodes and spill out at the edges of the resonator. Such behavior has been observed in the case of walls of water formed in an acoustic resonator at 1-G, where a fountain forms at the top of the water sheet which is formed (See Chapter 4). However it is not observed in the acoustic resonator with solid particles. Should this happen, then the appropriate course is to harden a coarse lattice of particles as soon as they reach the nodal plane, and allow subsequent particles to drift towards this lattice, and be heated so that they fuse with the lattice.

7.10 Fusing walls in place

A system for beaming intense sunlight (or converted beams of other wavelength) is needed. These beams will focus on small areas of the walls at a time, causing the surface material to melt and spread, in order to fuse the walls together.

7.11 Concluding remarks on the Radio Tailored Force Field for Construction

Several possibililties are opened up by the finding about radio waves for Space-based construction. These are summarized in Table 7.8.

Table 7.8: Basic issues and technical uncertainties in Waveguide TFF for Asteroid-Scale Construction

Basic issues	**Technical Uncertainties**
Low-cost transportation including Earth, Moon and NEA orbits.	Nature, power & cost of energy sources: *NEAs can be processed with focused solar energy*
Advanced tele-robotics. Imperative for Space resource utilization	Composition of Near-Earth Asteroids: *Ice for microwave blasting/ ionization/ liquid wall formation in artificial gravity? Ferromagnetic?*
Large-scale, diverse manufacturing at extra-terrestrial sites	Pulverizing asteroids without leaving harmful radioactive particles. *Microwave? Direct solar heating*
Low-gravity manufacturing sites to reduce transportation hurdles	Material / technology to make efficient waveguide shells (*i.e., metallic surfaces? Frequencies? Optical resonance? Inflatable Mirror arrays?*
Economic imperative.	

The needed solar energy can be collected using large-array Space mirrors [20]. While such construction may be scientifically feasible, any architecture to reach that horizon must first deal with nearer-term issues of building a Space-Based Economy- which will provide the “how” and “why”.

8. Opportunities& Outreach related to this project

8.1 Developing Space Experiment Opportunities

Student teams working with the PI have been developing two experiments for flight opportunities on the Space Shuttle. The first is a "Student Experiment in Microgravity" (SEM) module, which is scheduled for the next opportunity to launch a powered SEM module. The experiment is a cylindrical acoustic resonator containing Styrofoam balls, with ports in the cylinder at the expected nodal planes to inject liquid epoxy resin after the sound field is turned ON. The entire experiment has to be miniaturized, and packaged inside a small container, with total automation including feedback control of the resonant frequency.
The objectives here are

1) to record video of the formation of a solid wall, and its dynamic characteristics in the relatively clean microgravity environment of the Shuttle (expected g-jitter less than 0.01g)
2) to return a solid sample for structural and material analysis of objects formed using acoustically tailored force fields.

Prototype integrated circuit boards are being built for final testing.

The other experiment opportunity is a Getaway Special (GAS) module. Here, a deposit has been paid, and we are on the waiting list – but the GAS program is itself facing uncertainty. The payload in this case can be around 80 lbs, with a larger resonant chamber. The effort at this point is mainly on design and documentation, to obtain experience with payload development on this scale.

8.2 Papers & Presentations

1. Ganesh, B.A., Komerath, N.M., "Large-Scale Construction for a Space-Based Economy", In Laubscher, B.E., et al, (Ed). "Space 2002/Robotics 2002" Proceedings of Space '02, ASCE Conference on Space Manufacturing ASCE, March 2002, pp.262-268.

2. Komerath,N.M., Wanis, S.S., Ganesh, B.A., Czechowski, J., Tailored Force Fields for Space-Based Construction" Invited Seminar, National Reconnaissance Office, Washington DC, July 2002.

3. Komerath, N.M., Wanis, S.S., Czechowski, J., "Tailored Force Fields for Space-Based Construction". STAIF-02-084, accepted for publication in the Proceedings of the STAIF conference, Albuquerque, NM, February 2003.

4. Komerath, N.M., "ISS To Island-1: Synergistic Architecture For A Space-Based Economy" Proceedings of the Space Resources Utilization Roundtable, Houston, Texas, October 2002.

5. Gopalakrishnan, P., Wanis, S., Changeau, D., Dierks, C., Zaidi, W., Hardy, J., Rangedera, T., Rupnarine, D., Sharpe, I., Tsuda, M., Komerath, N., "To Mars and Beyond". Georgia Tech Team Proposal to the 2003 NASA Means Business Competition. November 2002.

8.3 Outreach

Table 8.1 Student participation

	Student Status	
Joseph Czechoswski	Junior, College of Computing, GIT	CATIA drawings, design and stress analysis issues in the construction of the Habitat in Lunar L-2
Balakrishnan A. Ganesh	PhD candidate, School of AE, GIT	Space-based economy and costing issues
Priya Gopalakrishnan	M.S. candidate, School of AE, GIT	Space-based economy and costing issues; NMB Team leader
Joshua Hardy	Senior, School of AE, GIT	Radio wave use in TFF
Sam Wanis	PhD candidate, School of AE, GIT	Acoustic Shaping issues, development of theory to predict generalized TFF.
Waqar Zaidi	Junior, School of AE, GIT	Graphics & Animation
Mitsuyo Tsoda	Freshman, School of AE, GIT	NMB proposal team
Ian Sharpe	Junior, School of EE, GIT	NMB proposal team
Carrie Dierks	M.S. Candidate, School of Literature, Communications and Culture, GIT	NMB proposal team
Dominique Rupnarine	Junior, School of EE	NMB proposal team
Tyson Stuart	PhD candidate, School of EE, GIT	SEM circuit design
Thilini Rangadera	Freshman, School of AE, GIT	NMB proposal team
Donald Changeau	Graduate Student, School of Technology & Public Policy, GIT	NMB proposal team

- Laura Healey, PhD candidate in Fashion Design from London, UK, is working with us on exploring the use of Tailored Force Fields in designing new fabrics and custom fitting of shapes. She has submitted a proposal to the British / European Space Agency for a project to explore these issues, and has agreed to serve as a user of our TFF design software.

- The Georgia Space Grant Consortium's is helping to present our work to Georgia-area schools.

- Media coverage of the TFF work has excited considerable public interest worldwide. These are summarized below.

8.4 Media Coverage

1. "New Scientist", a well-known British publication, has done two articles over the past 2 years describing first our "Acoustic Shaping" work ("Out of Thin Air", Sep. 2001) and the Tailored Force Fields work ("Rubble-Rousing in Space", October 11, 2002).
2. These articles have excited considerable interest, worldwide, showing a very high level of public interest in the prospects for developing business and living environments beyond Earth. Some examples are in Items 3 and 4 below.
3. "Josh" Magazine, New Delhi. Recently, an article has appeared in "Josh", a children's magazine published in Hindi in New Delhi, describing the Tailored Force Fields work and its relevance to future habitats and economic opportunities in Space.
4. "Malayala Manorama", a Kerala (India) Based newspaper, has also presented a full-page Sunday Supplement article on the TFF work.
5. An on going interaction has been developed with the Astronomer community interested in Near-Earth Objects regarding ideas for developing extraterrestrial resources
6. United Press International, and a Danish science magazine have expressed strong interest in developing stories related to our work for young audiences.

8.5 Examples of public reaction to the idea of Tailored Force Fields

- **News Scientist, October 2002** "Radio gets rubble-rousing" BYLINE: Bennett Daviss http://www.newscientist.com/news/news.jsp?id=ns99992901

Radio waves could construct buildings in space 11 October 02 Bennett Daviss

"..Huge buildings could be conjured up in space using nothing more than focused radio waves to push individual components into place. Radio-controlled construction would get around one of the obstacles to colonising space - the need to ferry heavy construction equipment into orbit and support the people who will operate it... The scale does not daunt NIAC director Robert Cassanova. "We see the idea as a way to build very large structures in space economically and with a minimum of manual labour," he says. "If you're able to move materials using waves, you could eliminate the need for large numbers of astronauts and the infrastructure to support them"... "

- **Whitley Streiber's Unknown Country (Daily News of the Edge)** http://www.unknowncountry.com/news/?id=2042

How to Build in Space-If We Ever Get There 15-Oct-2002

"...Huge buildings could be built in space using radio waves to move the pieces into place. Radio-controlled construction would make it unnecessary to move heavy construction equipment into orbit. It would also eliminate the need for space-walking construction workers. ..

- **A/CC News about Minor Objects**

Asteroid/Comet Connection A Central Library of Links to News Direct from Asteroid/Comet Explorers & Reporters Everywhere http://www.hohmanntransfer.com/news.htm

“An article in the 12 October New Scientist, "Building in space using waves" [new link], reports Narayanan Komerath's proposal to NASA's Institute of Advanced Concepts (NIAC) to use focused radio waves as force fields to build large structures in space with minimal human labor. “... Concepts (NIAC) to use focused radio waves ... sending a squad of solar-powered radio ... NIAC has an abstract of Komerath's ... Force Fields for Space-Based Construction ...

- **http://www.ipkonfig.com**

Force Fields to the Rescue

Posted By: Brian @ 7:00 PM (MST)

“There have been quite a few sci-fi books that include or assume large work forces of spacewalkers for building stations and other large structures in microgravity. This is hazardous stuff; nasty momentum events, micrometeorites, cosmic rays, and space debris are all waiting to puncture, pulverize, or poach exposed human bodies (space suits are too flimsy for much more than minimal protection). Robots are expensive, somewhat fragile and slow-moving, and lack versatility. But it may be possible to tune radio waves to match the dimensions of construction components and shove them around and assemble them by remote control.
P.S. -- Sounds to me like a good way to clear out all the orbital crud now threatening satellites and launch vehicles. “

9. Summary of Issues Identified

During the course of this project, some special issues were identified, which went too far outside what we had the resources to study. These are discussed below.

9.1 Metal production on the Moon

As discussed in Chapters 5 and 6, the development of a Space-based economy is part of the process to create the demand which will make large-scale construction in Space relevant. One of the primary barriers to such development is the difficulty of estimating costs and risks of any such project. In this environment, a reasonable calculation of the return on investment becomes too difficult to develop, to the thoroughness required to present to investors. While this sounds mundane, it nevertheless makes all the difference between a systematic approach, and Darwinian evolution.

Surprising to us, but probably well-known to others who have gone before us – but buried in some report of long ago, was the finding that the ***cost of steel manufacture on the Moon*** was perhaps the most uncertain of all the costs in the development of the 2km-dia cylindrical radiation shield. The reason for this is that steel manufacture by usual processes ***requires hydrogen and carbon*** in substantial quantities – and neither has been found on the Moon. The cost of delivering each from Earth is highly uncertain. Previous efforts to estimate the cost has made highly conservative assumptions, such as the assumption that the marginal cost of delivering a pound of hydrogen or carbon to the Moon, as part of a massive delivery operation, is the same as that of construction, per lb, of a completed Space Station.

In the case of hydrogen, this ignores the equally high cost of water on the Moon – and the opportunity to sell off the water to other users in a synergistic development, thus recovering the shipping cost of hydrogen. The alternatives are:

1. Recover the hydrogen from the water using an ISRU (in situ resource utilization) purification and electrolysis unit. In this case, the cost of steel becomes critically dependent on the efficiency of this unit in recovering the hydrogen for re-use. Thus one critical need is for high-efficiency, low-cost solar-powered electrolysis units. We expect that these will be developed as part of the Mars exploration effort, since shipping costs to Mars are even higher, and sunlight is scarcer there.
2. Steel manufacture from ore using intense solar-generate heating and/or electric fields. Again, there is considerable research done in this field, which must be taken through costing.

In the case of carbon, the best alternative may be to substitute carbon with silicon in steel manufacture. Again, this is an area where some research has been performed, and perhaps this should be combined with the research on lunar production of pure silicon for solar-cell applications. Reducing the uncertainty in the cost of metal production would go a long way towards developing a credible costing structure.

9.2 Resonator / waveguide technology

This was the other area where our exploration reached a canyon of our ignorance, too deep and wide for us to bridge without outside help and substantial learning. We were somewhat surprised to find, in July, that experts who had reviewed our proposal had in fact NOT laughed off the extreme idea of building spaceships and habitats out of pulverized asteroids using electromagnetic waves – but were getting disappointed that we were spending our time studying the more mundane things such as building 2km diameter radiation shields near the Moon. Following this eye-opener, we surprised ourselves at how far we were able to reach in proving the feasibility of radio-wave Tailored Force Fields – to build large radiation shields out of pulverized asteroids. We used prior demonstrations on Earth (the Arecibo SETI transmission) as proof that the required power levels were achievable. We also showed that resonators have been used to obtain extremely high microwave power levels. However, to go beyond this stage in designing resonators, amplifiers and antennae suitable for Space-based construction, we need expert help. This is an exciting field of endeavor – the possibilities are truly endless. It must be left to Phase 2.

9.3 Cost linkage to comprehensive plan

As indicated by the above items, the ability to do costing is critical to answering the “feasibility” questions and to plan really large steps. This was perhaps not the case in the 1940s and ‘50s, because the arguments that adequate tools were unavailable, and that hostile nations were racing towards similar objectives, were adequate to drive fast progress. However, today it is expected by the public. Thus a substantial effort in driving towards the TFF technological goals must be spent on developing cost, identifying technology options using cost considerations among others, and selecting the most effective path. This becomes critical because of the realization that only a synergistic effort involving many diverse projects and interests, can lead to such progress in a reasonable time.

9.4 The Microwave Demonstrator experiment

A major outcome of our study is that it is now possible to link phenomena across the acoustic, optical, microwave and radio wave domains of wave phenomena. For various reasons, discussed in the Phase 2 proposal, the microwave regime is the ideal one for an initial Space demonstration of construction in Space using electromagnetic fields. The technology for developing high-power microwave transmitters with excellent beam control is receiving considerable attention in the literaure. A recent example is Shaposhnikov [54].

10. Conclusions

At the core of this project is the realization that solid objects ranging in size from millimeters to kilometers can be assembled automatically into specified complex shapes using potential force fields. *Interesting shapes can be tailored using the standing waves of an unsteady potential force field. A multitude of objects can be made to simultaneously arrange themselves along specified surfaces. We have demonstrated this concept in microgravity flight and ground-based experiments. Tailored Force Fields (TFF) could work over a wide range of sizes and force fields. Specifically, this enables the primary goal of NASA's HEDS Grand challenge: the development of* "safe, fully self-sustaining integrated human and robotic presence in space and on other planets, independent from Earth and for indefinite periods of time".

10.1 Conclusions reached in the Phase 1 project

1. Tailored electromagnetic force fields enable massive automated construction at low recurring cost.
2. Theoretical approaches to acoustic, optical and electromagnetic force fields have been unified into a common Rayleigh regime prediction capability.
3. The use of resonators offers a large (3 orders of magnitude) increase in radiationforce, and upto 7 orders of magnitude increase in trap stability.
4. Acoustic shaping proven in flight and ground experiments.
5. Optical trapping has been proven in microscopy.
6. Microwave and radio wave TFF are efficient in solar-power usage for construction.
7. Costing using a Space-Based Economy approach illustrated using the middle term radiation shield project.
8. Quasi-steady magnetic fields enable telepresence-controlled construction of the radiation shield for human settlements near Earth.
9. Overall cost becomes practical when lunar- and Space-based industries are included.
10. Unlike exploration-focused government programs and isolated business plans for private ventures, a Space-Based Economy approach can unite public support for Space enterprise.
11. As more business visions are enabled by the assurance of a massive market provided by the infrastructure project, the level of public funding needed comes down, even before tax revenues.
12. Coherent plan needs to be articulated for developing a mutually-supportive network of economically-useful projects, with synergistic markets, risk evaluation and pricing.

10.2 Application Relevance

Previous conceptual studies of large human colonies away from Earth [1-2] have answered several of the concerns expressed by NIAC reviewers.

Why think of a Space-Based Economy at all? Today's Space programs are driven to miniaturization by the Launch Cost Barrier. Today's generation must face the reality that only a few Government employees and billionaires will fly in Space in the next 20 years under present plans. Public support for the Space program appears to have peaked. Competing Mission Plans fight for a declining pool of Science dollars – destroying each other. Our solution [6-10] is in resonance with strategic planners [1-2,11] – a coherent, synergistic plan for a *Space-Based Economy* – one where the Suppliers, Raw Materials, Infrastructure, Manufacturers and end-users are all away from Earth, with little dependence on Earth for bulk materials.

Why Build Large Settlements in Space? For the same reasons why humans quit living in caves or tents in the boonies, and move to big cities. Economies of scale. Scope for derivative / advanced professions. Co-location of essential facilities. Shared concern over problems – shared cost of solutions. Better living standards. The critical population size to make a Space colony viable as an economic entity is estimated to be in the several thousands [4] *Why not on a planetary surface?* There is no sense in commuting from the gravity well of the lunar surface if one's job is, say, maintaining satellites or power plants in GEO. The main attraction of a lunar cave is protection from radiation – a problem being solved here.

Other findings: Within a generation, the "unnatural" aspects of living in variable-gravity will have become "natural". Project times of 10-20 yrs and $100B budgets are acceptable – the ISS was started circa 1984 with completion scheduled for 2005, with total program cost [12]over $100B – with no promise of rapid economic expansion in Space. We tie our project into a comprehensive plan for a Space-Based Economy.

11. Acknowledgments

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