Use of Radiation Pressure for Space-Based Construction

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Abstract

The use of tailored electromagnetic fields is considered to build solid-walled structures of specified geometry from random-shaped debris in Space. In previous work, a unified view had been established, linking experiments and theoretical results from optical, acoustic and long-wave electromagnetics to develop an expression for the acceleration per unit intensity on objects of given mass and size. The consideration was restricted to the Rayleigh scattering domain. This paper first uses the Rayleigh regime result to size the construction system for a 1-meter thick cylindrical radiation shield at 1 A.U. from the Sun. Next, the implications are explored, of exploiting Mie-regime interactions with beamed waves in this construction example. Order-of magnitude gains are obtained in acceleration per unit intensity, with the application being to position individual construction blocks in refining the construction.

Introduction

A fundamental issue facing the future of human ventures into Space is the construction of structures massive enough to provide long-term radiation shielding. In previous work we have investigated means of constructing such structures. (Komerath, 2001) and (Ganesh, 2002) considered the use of quasi-steady magnetic fields to build a 2-meter-deep outer structure for a 1 km-radius, 2 km-long cylinder at a Lagrangian point of the Earth-Moon system. This is sufficiently close to Earth-based resources that telepresence could be used to control and fine-tune the lunar resource extraction, shipment and assembly of the structure. For construction at distances too large for telepresence, other means must be considered. We considered the possibility of using a resonant field of radio waves to move pulverized rock into a cylindrical-shaped wall. This appears appropriate for the construction of a radiation-sheltered outer wall of a station at one of the Lagrangian points L4 or L5 in the same orbit as Earth around the Sun. These regions are believed to hold a large number of solid objects of various sizes and compositions in stable orbits for durations of thousands of years, possibly including metallic objects, and carbonaceous objects with water ice inside. The technique we describe is also appropriate for constructing large vehicles to serve as Cyclers for routine transport to Mars or other solar system destinations. Being sufficiently far from large gravity centers, the “jitter” due to other forces was shown to be well under 1 micro-g, “g” being the acceleration due to gravity at Earth’s surface. Thus, sustained accelerations of 1 micro-g are adequate to cause objects to drift into position over a few minutes, to form a cylindrical wall 50 meters in diameter. Sample calculations are shown in (Komerath, 2004).

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Experiments in reduced gravity have shown that by tailoring potential fields a large number of particles can be moved into position along specified wall shapes in an acoustic field (Wanis, 1999). Work on the interaction of wave fields and particles has been driven by various applications in different parts of the spectrum, as seen from (Barmatz, 1982), (Brandt, 1989), (Torr, 1984). The present authors (Komerath, 2003) established a simple estimation for the acceleration per unit intensity which would act upon a particle of given size, unifying observations related to acoustic, ultrasonic, optical and microwave fields. The particle size was limited to 5% of the wavelength to stay inside the Rayleigh scattering domain. An example is shown in Figure 1, where we see that the acceleration per unit intensity drops with increasing wavelength.

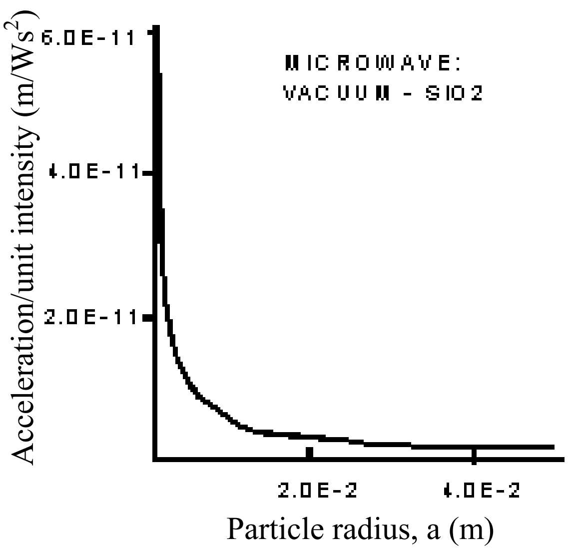

Figure 1. Variation of acceleration per unit incident intensity with particle radius in the Rayleigh regime.

Radiation Force

A general relation expressing the radiation force, *F*, due to any type of wave motion in any isotropic medium is (Joyce, 1975):

$$F = \frac{W}{c} = \frac{E\dot{x}}{c};$$

where W is the power carried in the wave, E is the energy/length, $\dot{x}$ is the energy velocity, group velocity or particle velocity, c is the speed of wave propagation. Ashkin (Ashkin, 1970) utilized radiation pressure of a laser beam to accelerate and stably trap micron-sized particles. Here the radiation force is

$$F_{rad} = \frac{2qP}{c}$$

where q is the fraction of light effectively reflected back, P is the laser beam power in watts, and c is the speed of light in the medium surrounding the particles. Forces up to $6.6x10^{-10}$ N were achieved, yielding accelerations on the order of 10^5g. It was found convenient to distinguish the radiation force by its two components: the *scattering force* and the *gradient force*. The scattering force is proportional to the scattering cross section of the particle, and thus proportional to the intensity of the incident wave. For scalar polarizability the force is in the direction of the Poynting vector. This force is due to the removal of momentum from the incident beam and is non-conservative (Ashkin, 1983b). The gradient force is due to the interference of the scattered field with the incident field, and is proportional to the in-phase component of the particle's polarizability. This force is the same as that which would arise from an electric dipole and thus attracts the scatterer (electric dipole) to regions of highest intensity, i.e. points in the direction of the intensity gradient ∇I. The gradient force is a conservative force whose potential is the free energy of the particle (Ashkin, 1983b). For stable positioning of particles a force equilibrium must be generated in all directions so that the particle would rest at the bottom of the potential well. The depth of the potential well is proportional to the incident intensity. The steepness and the shape of the potential well are governed by the intensity gradient ∇I (Rohrbach, 2001).

Scattering Regime Analysis

Studying the physics of scattering off particles in a tailored force field is essential to the proper design of a future space-based construction facility. For electromagnetic force fields Mie's theory (Grandy 2000) for scattering is applied to a dielectric sphere in an electromagnetic force field. The removal of momentum from the incident field by the particle corresponds to absorption or scattering. However, the radiation force on the particle is a result of the forward momentum transferred to the particle. If the particle diameter does not exceed 5% of the wavelength (*Rayleigh* scattering), the leading order terms dominate the partial-wave series, and thus provide simple analytic descriptions of the force. Here the scattered intensity is proportional to λ^{-4}. For particle diameters comparable to the wavelength, the full Mie scattering analysis must be used. Plots of the scattered intensity vs. angle are shown below to demonstrate the characteristic differences between Rayleigh and Mie scattering regimes. Plots were created in MiePlot v3.3.04 (Laven, 2002). The material was assumed to be granite (with a real relative dielectric constant of 3 at radio frequencies), the surrounding medium being the vacuum of space, with dielectric constant of 1. Particle radius is taken to vary from 0.1m to 1m corresponding to Rayleigh and Mie scatterer's respectively. The maximum wavelength of operation to be used is 2m (150 MHz). It is clear that scattering in the Mie regime offers significantly higher forces – 5 orders of magnitude higher – then Rayleigh scattering.

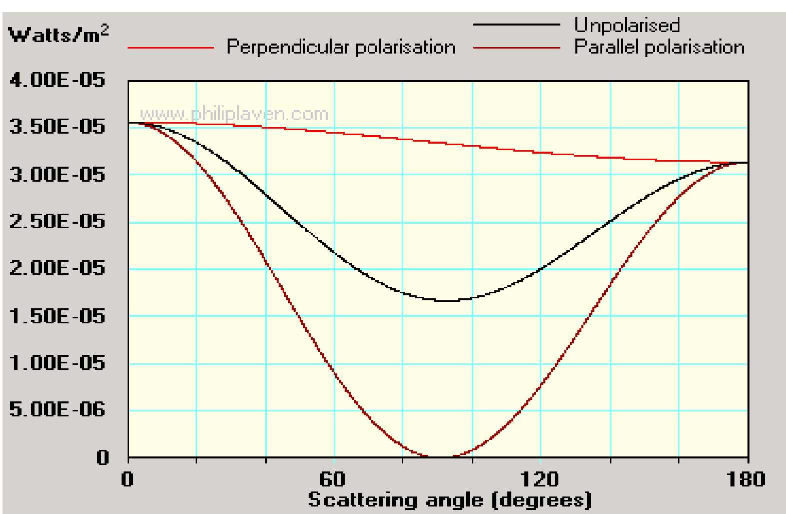

Figure 2. Scattering intensity vs. scattering angle for a 1 W/m^2 incident wave measured at a distance 1m away for a Rayleigh particle (10 cm radius).

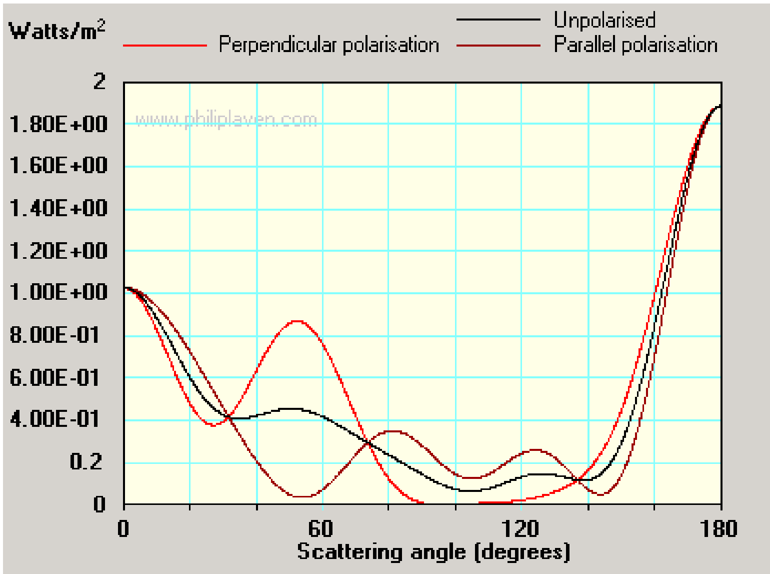

Figure 3. Scattering intensity vs. scattering angle for a Mie particle (1 m radius)

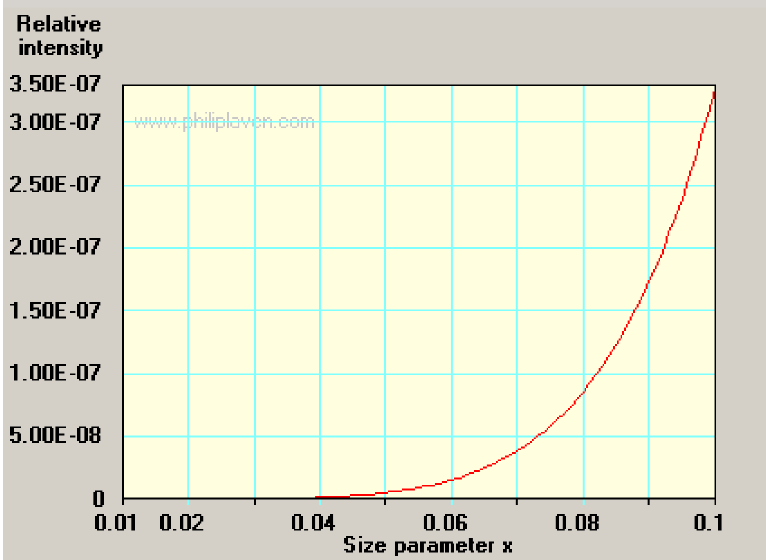

Figure 4. Rayleigh regime plots showing the variation of intensity scattered in a specific direction (180^o) with size parameter $x=2\pi a/\lambda$, where a is particle radius and λ is the wavelength measured in vacuum.

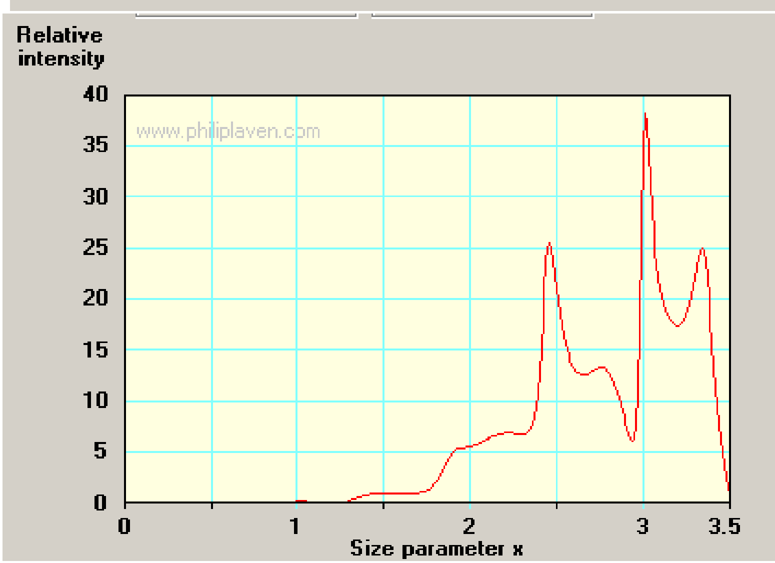

Figure 5. Mie regime plot of relative intensity as a function of size parameter, $x = 2\pi a/\lambda$. Note: Amplitudes of the scattered field are given from the calculated amplitude scattering function, and thus do not have physical significance other than for comparisons of the form of the variation.

For acoustic force fields, the analysis procedure is similar yet is simpler in the sense that we are solving for scattering of scalar waves. Expressions for the radiation forces produced on a particle scattering an incident wave are as follows for electromagnetic (Ashkin, 1986) and acoustic (Wang, 1998) fields, respectively:

$$F_{scat} = \frac{I_o}{c}\frac{8\pi}{3}k^4a^6\left(\frac{m^2-1}{m^2+2}\right)^2 \qquad\qquad F_{scat} = \frac{11}{8}\pi\frac{P_o^{\,2}}{\rho_o c_o^{\,2}}k^4a^6$$

where, I_o is the electromagnetic intensity, m is the relative refractive index of article to medium, P_o is the pressure amplitude in the sound wave, ρ_0 is the ambient density; and for both expressions, k, a, c are the wavenumber, particle radius, and speed of wave propagation, respectively. Notice the similar dependency of both forces on k^4a^6. It should be noted that this serves as a first step in the calculation of forces acting on the particles being positioned in the force field. The effect of setting up a resonant field greatly enhances the scattering forces by orders of magnitude. This is seen in the below equation for the acoustic radiation force on a rigid sphere in a resonant one-dimensional field.

$$F_{s\tan ding} = -\frac{5\pi}{6}\frac{P_o^{\,2}ka^3}{\rho_o c_o^{\,2}}\sin(2kz)$$

This force pushes the particle towards the pressure nodes ($z = 0$ and half wavelength integer multiples away). A force potential can be defined such that $F = -dU/dz$. For small values of kz, i.e. distances away from the nodes small in relation to the wavelength, the $sin(2kz)$ can be approximated by $2kz$. Thus, the radiation force then becomes similar to similar to a spring force with a "spring" constant equal to $-\frac{5\pi}{3}\frac{P_o^{\,2}ka^3}{\rho_o c_o^{\,2}}k$ the keeps the particle stable at the nodal locations, i.e. down the potential well, see Figure 6.

Likewise in an electromagnetic force field, as described above, there can also exist a gradient force (Ashkin, 1986) and corresponding gradient force potential given by:

$$U_{grad} = a^3\left(\frac{m^2-1}{m^2+2}\right)\frac{E^2}{2}$$

In what follows we perform an order of magnitude analysis outlined in (Ashkin, 1986) for estimating the stability of the particle in the potential well. As a sufficient trapping condition we set the ratio $U_{grad}/U_{noise} > 10$. We define U_{noise} as the energy imposed on the particles while inside the potential well due to irradiance from solar wind. This is done by considering the spherical particle embedded in a flow of solar wind photons. Solar wind pressure, P_w, is estimated (McInnes, 1999) as $P_W \approx m_p \rho \upsilon_W^2$, where m_p is the mass of a photon, ν_w is the solar wind speed about 700 km/s, and ρ is the mean photon number density. This yields a P_w = 3E-9 N/m^2.

Applying Stokes flow theorem to this situation, we get a force, $F_{stokes} = 4\pi r^2 P_w$. Together with the conservative solar wind speed given above, we get a U_{noise} equal to 6.6E-5 Watts. For a 10 W beam power the condition of $U_{grad}/U_{noise} > 10$ would be met.

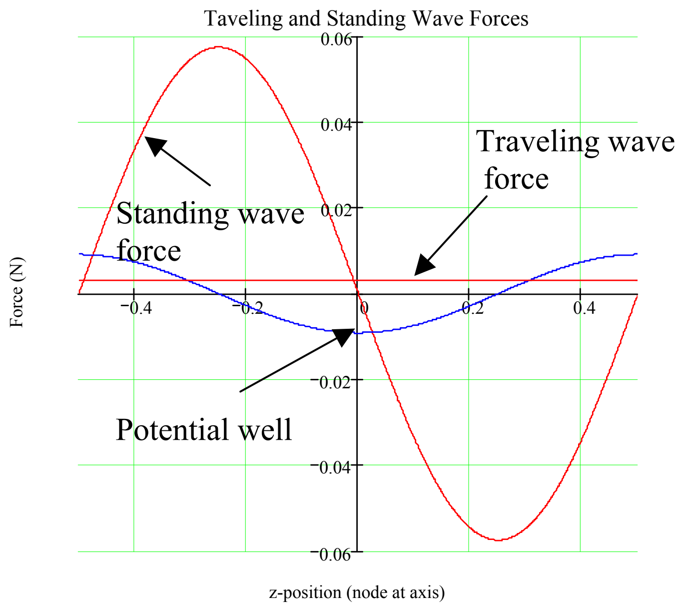

Figure 6. Comparison of traveling and standing wave scattering forces. Also shown is the standing wave potential well

Interactions between particles have been observed in the context of optical binding (Burns, 1989) The energy of interaction of two optically coherent induced dipole moments depends inversely on separation distance multiplied by an oscillatory factor This leads to optically induced, self-organized bound states of the two dipoles with stable separations every wavelength at the positions where the induced force is zero and the interaction energy is a minimum.

One observation from our previous acoustic experiments is that once the field is on and the particles tend to their stable locations, they seem to be accelerated towards each other as they get closer to each other. This occurs until a “wall” is formed - made up of individual particles. The best explanation for this is the Bernoulli attraction between them, due to the flow pattern setup between two particles in close proximity. Other possible forces involved in an acoustic resonant field are Oseen forces, which are due to the waveform distortion and consequent presence of harmonic content (Hueter, 1965).

Application to Space Based Construction

In the radiation shield application mentioned in the Introduction, Near-Earth Object (NEO) material, pulverized to an average particle size of 0.1m radius, is formed into desired shapes using the radiation pressure and gradient forces experienced by dielectric objects in a standing-wave field of radio waves, as conceptually sketched in Figure 7.

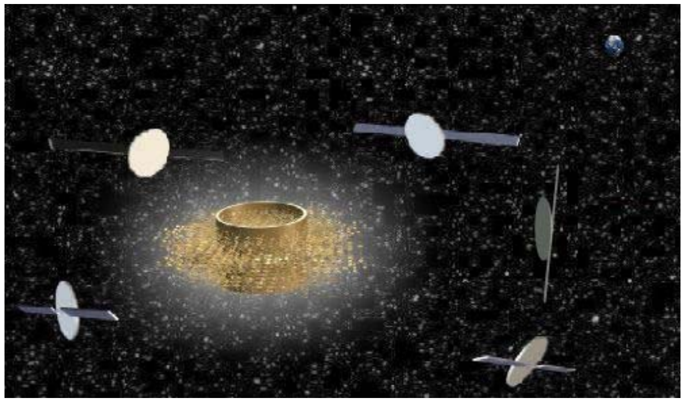

Figure 7. Conceptual drawing of a large radiation-shield being formed using radio waves, from pulverized asteroidal material. Earth is shown much larger than it would be seen from the Near-Earth Object region at the Earth-Sun L-5.

The radio wave field is produced by solar-powered transmitter/antennae which are positioned in formation around the particle cloud to set up a resonant field of the desired mode. As a test case, formation of cylindrical shells is considered. Once in position, the particles are fused by solar-powered energy beams through a sintering process. As seen above from the Rayleigh and Mie calculations, it is clear that Mie scattering offers higher forces by orders of magnitude. The large cylindrical shape is conveniently formed using Rayleigh scattering of long-wavelength radio waves, from a cloud of random-shaped stones. Once formed into a crude cylindrical shape, gravity helps to keep the shape stable, and thus reduces the field required. Focused beams of shorter-wave radiation (microwaves) would then be used to relocate and manipulate individual blocks into position using the larger accelerations available from Mie scattering.

Depending on the materials available, several other techniques could be used, at different wavelengths – noting that the dielectric constant is a strong function of wavelength. Radiation at suitable wavelengths (generally much shorter than the radio waves used for positioning) would heat parts of the material to melting point. Alternatively, a binder material may be found which can be melted even as the larger blocks are drifting into position, to form a solid wall. Absorption crossovers in a resonant electromagnetic cavity are discussed in (Jackson, 1991).

Conclusions

Mie scattering offers a five order of magnitude enhancement in the acceleration per unit intensity on the construction particles. As outlined above, this offers greater control over the particles during the construction procedure.

In the range of wavelengths considered in this project, dielectric materials suitable for construction experience variation in the dielectric constant that varies only slightly with frequency. This ensures that the frequencies used for collecting the particles into the desired shape are very far from the frequencies used to heat them.

The realization that such tailored force fields are indeed within practical conception is new. Further work is needed to brainstorm the implications of this finding, and develop architectures for exploiting this finding. The needed solar energy can be collected using large-array Space mirrors (Chilton, 1977).

References

Ashkin, A. et al. (1986). "Observation of a single-beam gradient force optical trap for dielectric particles," Optics Letters, Vol. 11, No. 5.

Ashkin, A., Gordon, J. (1983)."Stability of radiation-pressure particle traps: an optical Earnshaw theorem," Optics Letters, Vol. 8, No. 10.

Ashkin, A. (1980) "Applications of Laser Radiation Pressure," Science, Vo. 210, 5.

Barmatz, M. (1982) "Overview of Containerless Processing Technologies," in Materials Procesing in the Reduced Gravity Environment of Space. Published by Elsevier Science Publishing Co.

Brandt, E. (1989) "Levitation in Physics," Science, Vol.243.

Burns, M., et al. (1989) "Optical Binding," Phys. Rev. Let. Vol. 63, No. 12.

Chilton, F., Hibbs, B., O'Neill, G., Phillips, J. (1977) "Electromagnetic Mass Drivers". In O'Neill, G., Ed., "Space-Based Manufacturing from Nonterrestrial Materials".Prog. in *Astronautics and Aeronautics*, **57**, AIAA.

Ganesh, B., Komerath, N. (2002) "Space 2002/Robotics 2002" ASCE, pp. 262-268.

Grandy, W. (2000) "Scattering of Waves from Large Spheres," Cambridge University Press, NY.

Hueter, T., Bolt, R. (1965). "Sonics," John Wiley & Sons, Inc., NY.

Jackson, H., Barmatz, M. (1991). "Microwave absorption by a lossy dielectric sphere in a rectangular cavity," J. Appl. Phys. **70** (10).

Komerath, N., Wanis, S. (2004). "Radio Waves for Space Based Construction," in proceedings of *Space Technology and Applications International Forum (STAIF 2004),* edited by M. El-Genk, AIP Conference Proceedings, Albuquerque, NM.

Komerath, N., Wanis, S., Czechowski, J. (2003) "Tailored Force Fields for Space-Based Construction," in proceedings of *Space Technology and Applications International Forum (STAIF 2003),* edited by M. El-Genk, AIP Conference Proceedings 654, Albuquerque, NM.

Komerath, N., Ganesh, B. (2001). "Electromagnetic Construction of a 1km-radius Radiation Shield in Orbit." "High Frontier" Proceedings of Space Manufacturing 13, Meeting of the Space Society, Inc., Princeton, NJ, pp. 151-159.

Laven, P. (2003). © MiePlot v3.3.04, (www.philiplaven.com), updated 16 October.

Rohrbach, A., Stelzer, E. (2001). "Optical Trapping of Dielectric Particles in Arbitrary Fields," J. Opt. Soc. Am. A, Vol 18, No. 4.

Torr, G.R. (1984). "The Acoustic Radiation Force," Am. J. Phys. **52** (5).

Wang, T., Lee, C. (1998) "Radiation pressure and acoustic levitation," Nonlinear Acoustics, Academic Press, Chapter 6, pp. 177-199.

Wanis, S., Komerath, N., Sercovich, A. (1999). "Acoustic Shaping in Microgravity: Higher Order Surface Shapes," AIAA paper 99-0954, 37th Aerospace Sciences Meeting, Reno, NV.