Space–based magnetic driven liquid mirrors

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ABSTRACT

A description of the main results of a theoretical study on the required power and coils to drive a large ferrimagnetic liquid mirror are briefly sketched and discussed. A number of possible options are evaluated and a case–study for the International Space Station Alpha is also given.

1. INTRODUCTION

Liquid Mirrors Telescope has been proposed for large ground based telescope since a lot of time (see Ref. 1 for an historical perspective review) but only at the beginning of the century some serious attempt[2] has been performed. In more recent times a number of efforts[3] has been pushed in the liquid mirror technique.

The only space application to our knowledge consists in the testing of space optics using rotating liquid mirror on the ground. Nevertheless we've proposed[4] a technique to deploy a liquid mirror in space.

Large liquid mirrors in space can be generated by applying to the liquid mass a force such that the surface of the eso–potential corresponds to the required mirror's figure. In this framework Borra[5] proposed to use a centrifugal force by spinning the liquid mirror on a spacecraft permanently accelerated by a solar sail.

Alternative ways to drive a liquid mirror concern the forces produced by a magnetic field interacting with the current flowing in the liquid[6] or using the forces arising in a ferrimagnetic body (uninterested by an electrical current) embedded in a space–variable magnetic field[7].

Of these two last options the first has been proposed for an adaptive mirror (see also Ref. 4) and only as a remark it is mentioned the possibility to use the technique to deform large liquid mirrors. The second use strong magnetic fields to change the surface of a ground based spinning mirror from a parabolic to a spherical one. The option of an adaptive liquid mirror is also mentioned.

In the following some options for a large space–based liquid mirror telescope are outlined.

2. CONCEPT DETAILS

The force per volume unit $\mathcal{F}$ of a liquid with relative magnetic permeability χ_m embedded in a magnetic field H is given[8] by:

$$\mathcal{F} = \frac{1}{2}\mu_0\chi_m\vec{\nabla}(H^2) \tag{1}$$

Modelling the magnetic field in an enough large region, could provide a viable way to trap liquid particles in a well defined volume (see for example Ref 9). This basic idea, sketched in Fig.1. can be easily obtained for a concave region and a $\chi_m > 0$ adopting two circular coils.

The acceleration experienced by a liquid with density ρ located at $\frac{1}{2}R$ from the center of the first coil embedded in a magnetic field produced by a pair of equal coils having the same common axis, distant $2R$ each other, and interested by the same current, flowing into opposite directions, can be easily evaluated[10] and is approximately given by:

$$\tilde{a} \approx 0.3\frac{\mu_0\chi_m N^2 I^2}{\rho R^4} \tag{2}$$

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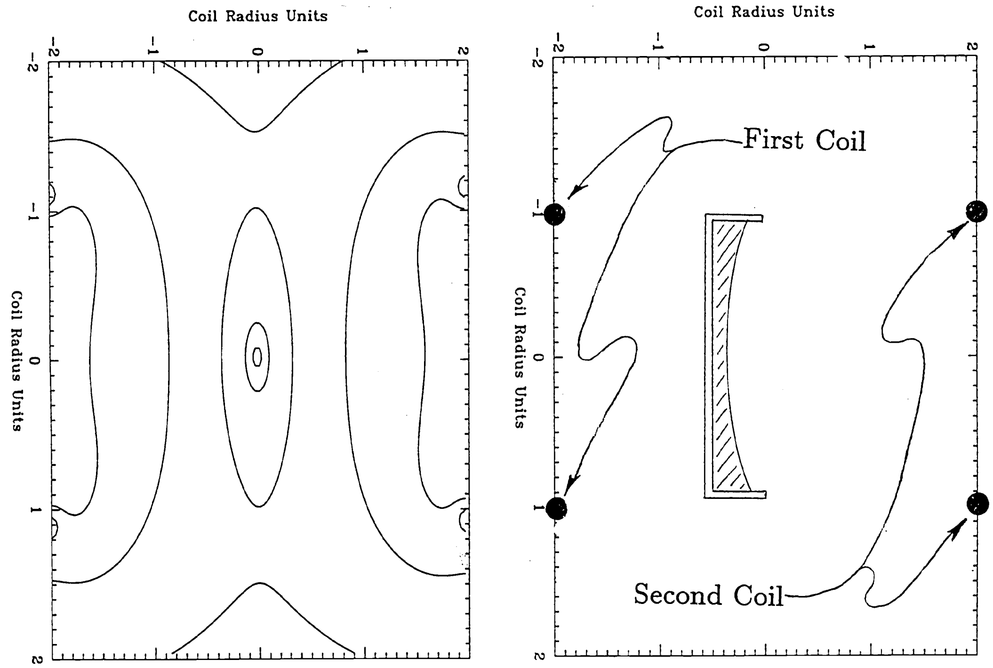

Figure 1: *Left*: The H^2 magnetic field generated in between two circular coils interested by the same current with opposite directions; *Right*: Placing a pot in the proper position the ferrimagnetic liquid, if other forces are negligible, can be confined with a concave free surface.

The detailed shape of the concave surface of the liquid mirror magnetically confined will be discussed later.

The required thickness τ of liquid mirror is obtained by scaling law given in Borra[5] with respect to the required thickness on the ground τ_g is given by:

$$\tau = \tau_g\sqrt{\frac{g}{\tilde{a}}} \tag{3}$$

where g is the gravity acceleration in standard ground–based conditions ($g \approx 9.81 m \cdot s^{-2}$).

The mass of the liquid mirror is derived in the following relationship:

$$M_m = \rho\pi\tau\beta^2 R^2 \approx \pi\sqrt{\frac{g}{0.3\mu_0}} \cdot \frac{\rho^{3/2}\beta^2 R^4}{NI\sqrt{\chi_m}} \tag{4}$$

where βR is the true radius of the liquid mirror. Feasible values for β lies in the range $0.5 \ldots 1$

The required power to maintain the mirror in the correct figure is given by:

$$P = \eta\frac{2\pi R}{S}NI^2 \approx \frac{2\pi}{0.3\mu_0} \cdot \frac{\eta}{S} \cdot \frac{\rho R^5 \tilde{a}}{N\chi_m} \tag{5}$$

where η is resistivity of the coils materials and S is the section of the coil wires.

The mass of the coils, assuming ρ_c the density of the coils material, is given by:

$$M_c = 2\pi NRS\rho_c \tag{6}$$

From the above relationships one can easily obtain $M_m/M_c \propto R^3$, that is for large diameters the mass of the coils will becomes negligible, so the results obtained by Borra[5] for the large mirrors case shouldn't be affected by the adoption of coils, at least for the problem of the amount of mass to be launched.

The acceleration $\tilde{a}$ not only defines τ and, by consequence, M_m, but it is also constrained by the pointing–induced accelerations a_p and gravity gradient acceleration a_g. The condition to be fulfilled in order to have a *stable* liquid mirror is that $\tilde{a} \gg a_p$ and $\tilde{a} \gg a_g$.

The acceleration a_p due to pointing requirements are given, at the edges of the liquid mirror, by the relationship:

$$a_p = \frac{4\varphi\beta R}{t^2} \tag{7}$$

assuming a constant acceleration/deceleration for a re–pointing spanning an angle φ over a time t.

The gravity gradient experienced by the rim of the mirror in a Earth–bound orbit, at height d is given by:

$$a_g = \frac{2gR_\oplus^2\beta R}{(R_\oplus + d)^3} \tag{8}$$

where $R_\oplus$ is the Earth radius.

Finally, in this rough approach, it is to be pointed out the effect due to the evaporation of the liquid that translates into a change in the shape of the free surface. This problem can be avoided, in principle, by changing the volume available on the rear side of the mirror or refilling in a nearly continuous manner the liquid amount.

3. SOME CASE STUDIES

In order to study in some detail the shape of the free surface of the liquid mirror magnetically confined we have written a code able to fit an isomagnetic surface with a revolution surface generated by a polynomial with the proper number of terms.

Given the characteristics of the coils (position, radius and current flow) the H field is calculated for a number of cells in a three–dimensional volume. When some symmetry can be found the calculation can be performed only on a bi–dimensional lattice. This last is the case, for example, of two coaligned coils. Nevertheless the code is able to deal with situations where such a symmetry is broken. This could be useful, for example, to study the requirements on the tolerances about coalignment of the two coils.

Given the position of the vertex of the liquid mirror concave surface, the related H value is found and interpolated over the whole interested region. Finally, this set of points is fitted with a polynomial surface and residuals are evaluated. In this way an iterative process, adding a new term at any iteration, is able to provide the best fit, with some given tolerances (e.g. a fraction of wavelength) with the minimum number of terms.

Usually this surface is a strongly aspheric one. With reasonable fit tolerances ($\lambda/4$) an approximate parabolic surface can be obtained only using a long focal ratio, that is very low values for β.

In order to obtain some optical configuration interesting for astronomical purposes, two ways are viable:

- the magnetic field is deformed by other electromagnetic coils and/or by the interposition of ferrimagnetic structures and the derived magnetic field shows a free surface closer to the required one (e.g. a parabolic or a slight hyperbolical one);
- the strong asphericity is corrected by a suitable optical solution where the input pupil is reimaged into another mirror where the correction can be easily performed.

The first option resembles the one proposed by Shuter and coworkers[7] and is not explored here. For the second option a possible optical design is sketched in Fig.2. Because of the strong asphericity required to counter–balance the one introduced by the liquid mirror, we have imposed that the pupil is reimaged onto a very small mirror and that such a reimaging is performed with purely spherical mirror. The solution shown in the figure is to be regarded only as a demonstration of the feasibility of such an approach. The optics is stigmatic on–axis while the aberrations behaviour dependence upon the field of view is to be studied.

In Tab.1 some realistic or futuristic cases of orbiting telescopes are listed. For all the 31 options ferrimagnetic mercury is assumed as the adopted liquid, while copper is the choice for the coils. No attempt has been given to the possibility to use superconductor operating at normal temperatures, being the related technology too young for a realistic utilization.

The data are clustered in three principal groups: mirror parameters, coils parameters and requested resources. From the first column the orbit type and the pointing rate can be inferred from the caption. The diameters of the clear aperture of the telescope are grouped into five classes: a 0.5m demonstrative solution, a IUE–like telescope, an HST–class telescope and a more futuristic 10m and 100m class telescopes.

Notes	Mirror data				Coil data			Requested resources			
	D[m]	τ[mm]	χ_m	M_m[Kg]	N	I[A]	S[mm^2]	M_c[Kg]	M_{TOT}[Kg]	M_{glass}[Kg]	P[W]
A	0.5	22	0.2	59	5648	0.1	3.2	309	368	34	6
	0.5	22	0.2	59	565	1	3.2	31	90	34	56
	0.5	22	0.2	59	57	10	3.2	3	62	34	560
	0.5	22	0.2	59	6	100	19.6	2	61	34	897
B	1.0	21	0.2	226	2513	1	3.2	279	505	300	507
	1.0	21	10	226	356	1	3.2	40	266	300	72
C	2.5	26	10	1825	18270	0.1	0.8	1288	3113	4600	374
	2.5	26	10	1825	18270	0.1	3.2	5152	6977	4600	94
	2.5	26	10	1825	3654	0.5	1.8	580	2405	4600	831
	2.5	26	10	1825	1827	1	3.2	515	2340	4600	935
D	10	13	10	14×10^3	5510	10	3.2	6×10^3	20×10^3		1000×10^3
	10	13	10	14×10^3	5510	10	19.6	38×10^3	52×10^3		176×10^3
	10	13	10	14×10^3	55100	1	19.6	380×10^3	394×10^3		18×10^3
	10	13	100	14×10^3	17400	1	3.2	19×10^3	33×10^3		35×10^3
	10	13	1000	14×10^3	5510	1	3.2	6×10^3	20×10^3		11×10^3
	10	13	1000	14×10^3	5510	1	19.6	38×10^3	52×10^3		1.8×10^3
D	100	4.2	10	446×10^3	1740000	10	3.2	19.2×10^6	19.6×10^6		3500×10^6
	100	4.2	100	446×10^3	551000	10	3.2	6.07×10^6	6.516×10^6		1100×10^6
	100	4.2	1000	446×10^3	174000	10	3.2	1.92×10^6	2.366×10^6		349×10^6
	100	4.2	10	446×10^3	17400	1	3.2	192×10^6	192×10^6		349×10^6
	100	4.2	100	446×10^3	551000	1	3.2	60.7×10^6	61.1×10^6		110×10^6
	100	4.2	1000	446×10^3	1740000	1	3.2	19.2×10^6	196×10^6		34.9×10^6
E	100	8.4	10	891×10^3	8710000	1	19.6	600×10^6	601×10^6		27.9×10^6
	100	8.4	100	891×10^3	2750000	1	19.6	190×10^6	191×10^6		8.81×10^6
	100	8.4	1000	891×10^3	87100	10	78.5	24×10^6	24.9×10^6		7.0×10^6
	100	8.4	1000	891×10^3	871000	1	19.6	60×10^6	60.9×10^6		2.79×10^6
	100	8.4	1000	891×10^3	8710000	0.1	19.6	600×10^6	$601. \times 10^6$		279×10^3
	100	8.4	1000	891×10^3	8710000	0.1	78.5	2400×10^6	2401×10^6		70×10^3
F	100	137.0	1000	14.5×10^6	5354	10	78.5	1.47×10^6	16.0×10^6		430×10^3
	100	137.0	1000	14.5×10^6	53540	1	78.5	14.7×10^6	29.2×10^6		43×10^3
	100	137.0	1000	14.5×10^6	535400	0.1	78.5	147×10^6	176.2×10^6		4.3×10^3

Table 1: For every case we have utilized a $\beta = 0.8$. **A**: low orbit, pointing rate of $11^0 \cdot \mathrm{min}^{-1}$; **B**: geo–synchronous orbit, pointing rate of $11^0 \cdot \mathrm{min}^{-1}$; **C**: low orbit, pointing rate of $6^0 \cdot \mathrm{min}^{-1}$; **D**: geo–synchronous orbit, pointing rate of $6^0 \cdot \mathrm{min}^{-1}$. **E**: geo–synchronous orbit, pointing rate of $3^0 \cdot \mathrm{min}^{-1}$. **F**: geo–synchronous orbit, no pointing option.

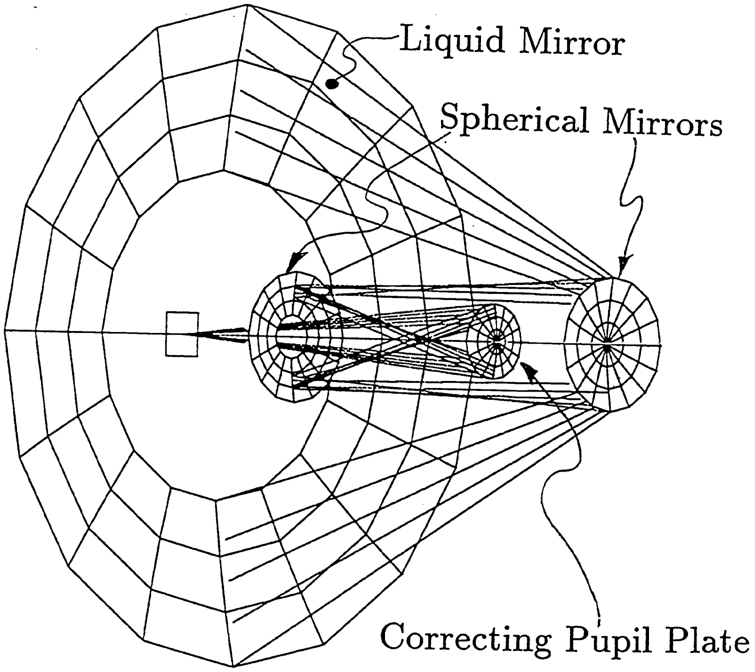

Figure 2: A possible optical configuration for a space–based liquid mirror telescope.

The different telescope diameters define also the different radius of the coils employed to model the mirror as given by:

$$R = \frac{D}{2\beta} \tag{9}$$

In the fourth column one can see how χ_m values in the current state of the art ($\chi_m = 0.2$) has been adopted for the smaller cases. For the HST–class case a slightly larger value $\chi_m = 10$ has been adopted, assuming that some improvement in the ferrimagnetic fluid technology can be achieved. For the long term 10m and 100m class orbiting telescope cases some examples adopting much larger χ_m values has been listed. It is worthwhile to point out that for solid materials such values can be easily achieved.

As it is possible to see from the fourth column we have employed different values of the magnetic permeability utilizing liquids much more ferrimagnetic for larger mirrors than for smaller one.

In the last columns a comparison has been attempted between liquid and traditional glass mirrors, with the exception of the 10m and 100m class where segmented or non–traditional mirrors are foreseen. The required power for setupping the mirror mass can be made enough small to become feasible with standard solar panels generator, at least for most of the options.

4. THE ADOPTION OF SUPERCONDUCTING COILS

In recent times the technology of relatively high temperature superconductors, like the *popular* Y123, has seen a dramatic improvement[11].

With the current state of the art it is not possible to foresee a large superconducting coil in space in order to drive a ferro–magnetic mirror. It is to be pointed out that large magnetic fields, as the ones required in most of the selected case studied, can easily destroy the superconducting properties of the used alloy.

Nevertheless in a more far future one can forecast a development in this technological branch to allow for gigantic magnetic driven mirrors with extremely low power consumption.

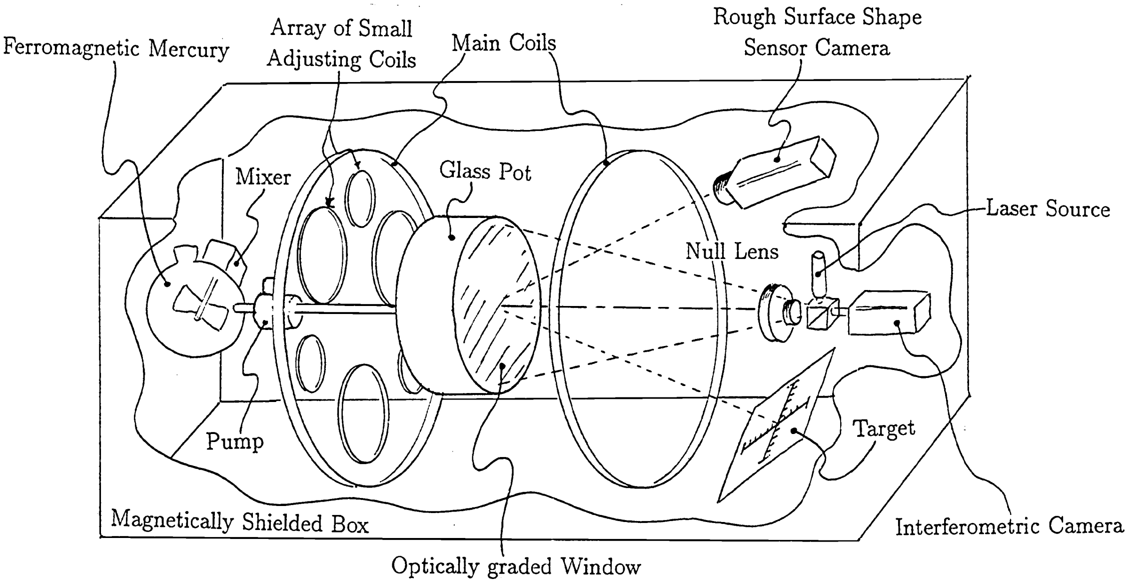

Figure 3: A possible layout for the on–board ISSA experiment.

5. A DEMONSTRATION MIRROR ON THE SPACE STATION ALPHA

United States, former Soviet Union, Europe and Japan will operate an International Space Station, called *Alpha* (ISSA) where a number of experiments both in pressurized and un–pressurized environment will be performed. In this paper we outline a demonstrative experiment in the framework of ISSA with the target of deploy and characterize a small (0.5 m) ferrimagnetic liquid mirror.

In the un–pressurized case the telescope could be used to track stars as they pass over the local zenith of ISSA, while in one of the micro–gravity experimental rack inside the pressurized volume one can think of a self–contained experiment where the mirror is checked in auto–collimation during the deployment in order to collect invaluable data over the characteristic of the surface under such environment.

The possible configuration of this last experiment is shown in Fig.3. In the drawing it is possible to recognize a number of elements that one can foresee for this experiment.

The ferrimagnetic mercury should be generated through mixing of small iron spherules with the mercury itself[12] by some mixing device. In fact, such spherules tends to decouple from the mercury due to gravity. During the launch such a mixture will experience a very hard gravity force that can leads to a substantial decoupling between the iron spherule. The pump will deploy the ferrimagnetic fluid into a glass pot closed by an optical window. During the deployment the two main coils will be switched on, while a rough surface shape sensor will image some target pattern through the mercury reflecting surface. The video–recording by such a camera will enable to reconstruct the deployment mechanism. When the fluid will be enough stabilized an interferometric system, through a proper chosen null–lens will give informations about stability and optical quality of the free surface. At this point an array of small adjusting coils can be switched on with some pre–determined amount of current and the technique to correct the shape of the mirror surface in a magnetic way can be easily tested.

6. CONCLUSIONS

In this paper we've given some possible ideas for a demonstrative experiment to be carried out in space environment. Nevertheless more futuristic cases has been also shown placing the magnetic driven liquid mirror options on a well established theoretical basis. Obviously the technological requirements to build such an instrument remain in the field of dreams.

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