Space Based Liquid Ring Mirror Telescope (SBLRMT)

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Abstract

There are several advantages and few disadvantages, of deploying a large Space Based Liquid Ring Mirror Telescope (SBLRMT). The two most significant problems facing large optics in space are weight and wavefront control. Liquid Mirrors go a long way to mitigating these two problems. They provide light (7kg/m2) primary mirror and 10 nanometer figure control passively. There are technology issues, but no physics show stoppers. Ground based 2-3 meter liquid mirrors routinely achieve 10 nanometer surface control. A liquid Ring Mirror works by spinning liquid mercury under the acceleration of gravity to produce a parabolic surface. This great performance is achieved without the expense of polishing or the complication of advanced metrology systems, and Liquid Mirrors are thermally stable. Unfortunate restriction of ground based mirrors is that they can only look straight up. Space based mirrors, however, don't suffer this restriction. Since there is no gravity in space thrust can work as a substitute for gravity as the source of acceleration. Additionally, spinning any object in space is relatively easy without the need for bearings, which only add vibration. This paper will discuss the benefits of a large liquid mirror in space as well as address some of the apparent issues.

History

Sir Isaac Newton was the first to propose that a rotating liquid creates a perfect parabolic surface. This can be verified by considering the vectors of centripetal force and gravitational force as illustrated in figure 1. The perpendicular components of the total force vector must balance each other, or the liquid will move. The result is a parabolic surface shape. The focal length of the mirror is a function of the acceleration (g) and the angular frequency (**w**) given by:

Figure 1) Ground Based Liquid Mirror Telescopes

Existing Liquid Mirror Telescopes (LMT) Around the World

- NASA Orbital Debris Observatory - 3.0m
- Liquid Mirror Telescopes at UBC - 2.7m (currently building a 5.1m)
- LMs at Université Laval - 2.5m (currently building a 3.6m)
- HIPAS LIDAR near Fairbanks (UCLA) - 2.7m
- Purple Crow LIDAR at UWO - 2.7m
- Liquid Mirrors at Centre Spatial de Liège - 1.4m

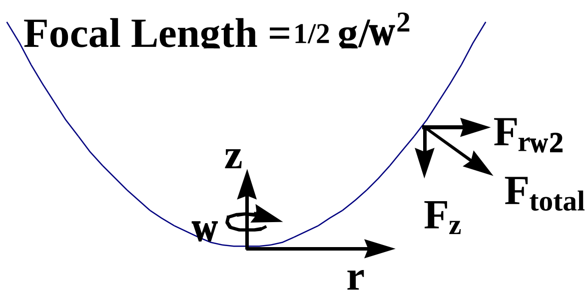
Parabolic surface is produced by spinning liquid mercury under the acceleration of gravity

Nature adjusts the surface automatically (passively)

- No thermal control or advanced metrology is needed
- Excellent 10 nanometer figure control

Limited to observing within a few degrees of vertical

8.2 m glass mirrors are created using this technique



Purple Crow

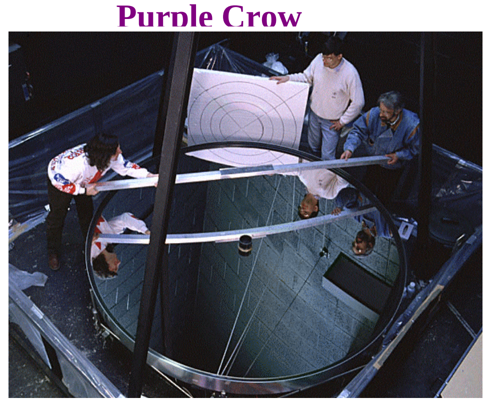


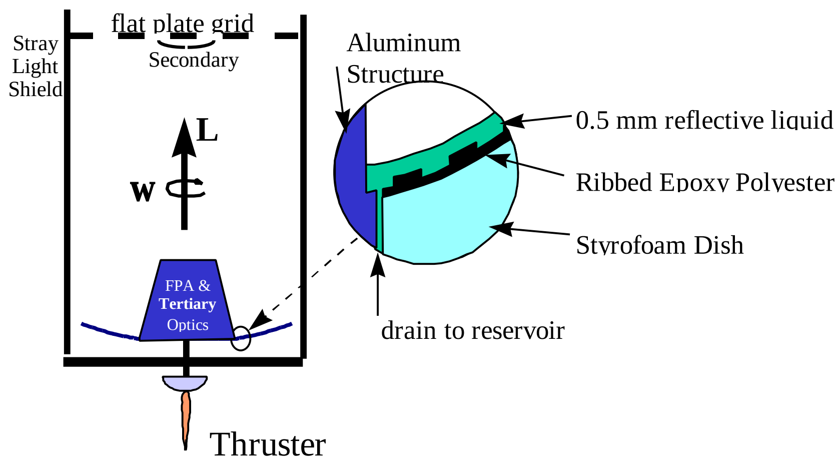
image courtesy of Purple Crow Lidar group, University of Western Ontario, London, Ontario, Canada

Because of the complexity and precision required to create this parabolic surface, a working limit would not be developed until 1872 when Skey constructed a working 35 cm Liquid Mirror Telescope (LMT). An obvious limitation with LMTs is that they cannot be tilted and consequentially cannot be pointed to track like conventional telescopes. This major handicap has made them all but useless to astronomy. Over the last 15 years LMTs have been developed for other applications, monitoring the atmosphere using a LIDAR. The technology has continued to develop and several diffraction-limited LMTs have been produced successfully, (see figure 1) and larger 5 to 6 meter telescopes are currently on the drawing board. Additionally, the world's largest 8.2 m glass primary mirrors are produced in a similar fashion by spinning molten glass in an oven and cooling it very slowly.

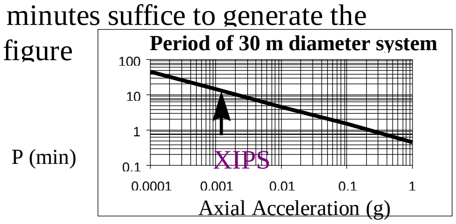
Dish

Because the reflective metal is heavy, the dish in formed as an approximate parabolic shape in order to reduce the amount of metal needed,(see figure 2). Styrofoam is used because of its low coefficient of thermal expansion, low mass density. Further, Styrofoam is easy to work with, and is inexpensive. The Styrofoam cone is supported by an aluminum frame (not shown) which also supports the metrology and control equipment necessary to retain the dish shape to within 0.1 mm. A thin epoxy polyester layer which has porous ribs covers the Styrofoam. The porous ribs help prevent the liquid from sloshing when the dish is being filled. A central tube sits at the bottom of the dish to drain the mercury.

Figure 2) SBLRMT Description



Milli-gravity thrust and one rotation in several minutes suffice to generate the optical figure



Primary Mirror Weight Estimate = 7 kg/m^2

- 0.5 mm gallium (specific gravity = 6.3g/cm^3)
- light weight structural support
- Styrofoam dish
- balancing metrology
- flat plate grid 1 mm glass (sp. g.= 2.4g/cm^3)

Univ. Laval researchers recommended Ga-In

- more reflective than mercury
- 1/2 the density of mercury

To minimize the weight and therefore the cost, and to help dampen effects of disturbances, ground based LMT have developed techniques that allow them to work with layers of mercury as thin as 0.5-mm. Researchers at the University of Laval (http://wood.phy.ulaval. ca/lmt/home.html) have proposed other liquids like GA-In eutectics. Ga-In density is 2.2 times lower than that of mercury; We should be able to make a very thin layer of liquid Ga-In which will diminish mechanical constraint and give better surface quality. An additional benefit is that Ga-In reflectivity is better than mercury's reflectivity. A layer of 0.5-mm of Ga-In covering the primary mirror surface adds a weight of 3 kg/m^2. A 1 mm layer of glass, required to maintain positive vapor pressure, adds a weight of 2.4 kg/ m^2. The necessity of the glass flat is discussed later in this paper. The additional weight of the Styrofoam, metrology, and other structural components bring the total primary mirror weight estimate to 7 km/ m^2.

Rotation Rate

The rotation rate of the primary, the thrust level, and the liquid stability are interrelated and this relationship will need to be studied in more detail. Figure 2 shows the relation between axial acceleration and the rotation period for a focal length/diameter = 1.0. One can see that for accelerations of about 0.001 g, the rotation period is just over 10 minutes. Xenon Ion Propulsion Systems (XIPS) which has just been demonstrated on DS 1, can sustain this level of thrust for months. The optical quality of the reflective surface depends mainly on vibrations and the vertical alignment of the rotation axis. Wobbling should be controlled accurately. Liquid-driven instabilities suppressed by porous sub-surface barriers and very thin (0.5 mm) liquid layers. Wave phase sensing and active damping will be required. We are assuming that the settling time is significantly longer as a function of lower thrust acceleration. A study needs to be performed as to the optimum liquid settling time /thrust/rotation rate relationship.

Operations

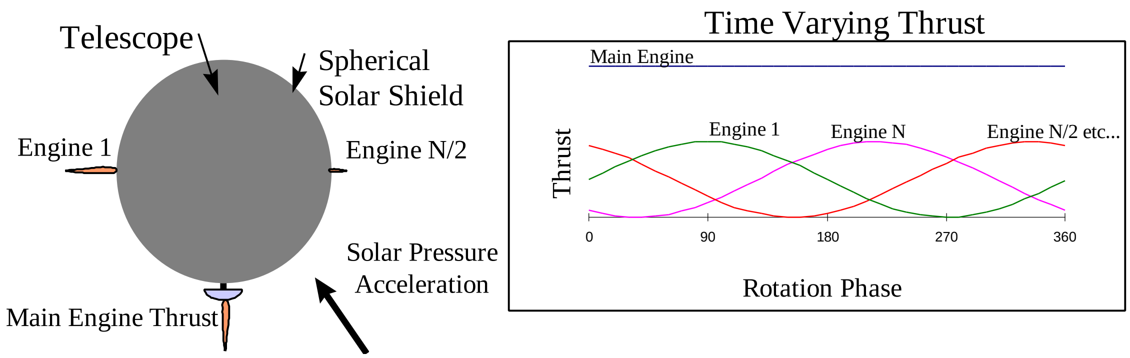
The thrust acceleration is along the angular momentum vector (L), which is an unstable equilibrium. It is extremely important to maintain torque = m $\mathbf{a}_{\mathbf{total}}$ X $\mathbf{L}$ = 0 to avoid precession (and wobble). We will have to be able to sense acceleration and L and respond in real time. The proposed space vehicle will be placed in a 1 AU solar orbit. We need to maintain a significant distance from the Earth and Moon tidal forces in order to minimize torque on the system. The telescope will need to maintain a relative 45- degree solar-exclusion angle in order to avoid excessive internal thermal load Micrometeors are bound to hit the mirror occasionally so there should be a robotic tender on the vehicle to repair holes.

In order to capture an image, the LRMT space module will accelerate towards the point that is being observed. It will then spin up to the proper angular frequency; balance the telescope; fill the primary with liquid and make an observation. When the observation is complete it will stop spinning and drain the liquid from the primary. At this point the telescope can be reoriented to a different observation point. Notice that the (FPA) is rotating slowly with the telescope.

Solar Pressure

One problem that will need to be overcome is that the whole telescope will act as a large solar sail. Solar pressure will induce torque if it is not acting directly through the center of gravity. Solar pressure induces transnational acceleration that must be accommodated. A valid approach to overcome these problems is to deploy a spherical solar shield centered on the system center of gravity (CG), see figure 3. Then apply a time varying thrust from auxiliary engines to compensate for pressure on the Solar Shield. We must sense and compensate for varying Solar Pressure both as a function of time and as a function of angle.

Figure 3) Overcoming the Solar Pressure Problem

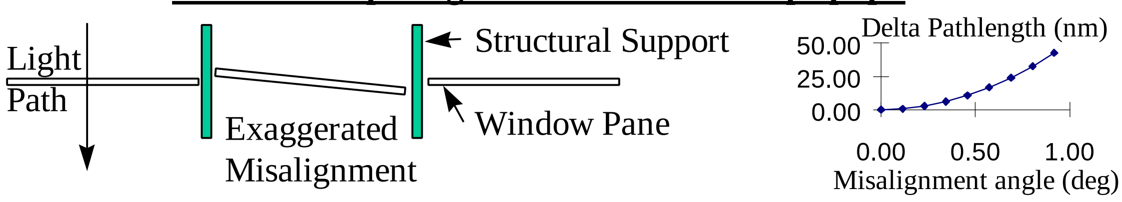


Vapor Pressure

Another problem that must be addressed is that liquids have a finite vapor pressure. When a liquid is placed in a vacuum, some atoms will evaporate or boil taking energy with them. This process will continue until the remaining liquid freezes. This is not good. The only immediately foreseeable solution is to maintain pressure, which is equivalent to the vapor pressure of the liquid. This will require a transparent seal on the telescope compartment. One approach that would work is to cover the telescope pupil with a grid of flat window panes. The flat plates would have to have a uniform thickness of 10 nanometers to avoid corrupting the wavefront. The panes could be mass produced on the ground and transported to space. We would generate small (20 cm x 20 cm) window panes to precise thickness. Fortunately, once the window panes are in place, no additional metrology is necessary on the pupil window pane grid as minor misalignments produce only a secondary corruption to the wavefront. If we can keep the alignment of the panes to within 0.45 degree, only a 10 nanometer optical path length difference would be encountered.

Figure 4) Liquids must be pressurized

Flat window pane grid that covers telescope pupil



Balancing and Damping

The reflective liquid will have instabilities, which will be suppressed by a porous sub-surface barrier. As it turns out, thinner liquids are more resistant to instabilities and that is one of the reasons for using only a very thin (0.5 mm) liquid layer.

Finally, the wave pattern can be sensed and actively damped. The damping time scale is much faster than any wave, and the wave frequency can be calculated and anticipated.

The telescope structure will have natural low frequency oscillations, which will be suppressed by passive energy-absorbing dampers. This technique is highly developed and the technology is mature.

In order to maintain focus and figure control, the acceleration must be monitored very precisely. A very fine thrust control will be required to compensate from any deviations from the ideal acceleration. DS-1 has recently demonstrated that Ion Propulsion (XIPS) thrusters provide precise, efficient thrust control. We think that a version of XIPS can be adapted to large scale telescope acceleration and control.

Other issues and trade studies

There are several other technology issues that need to be studied in depth. Fortunately none of these issues are Physics show stoppers. We need to have very fine control of the Xenon Ion Propulsion System (XIPS). XIPS' fantastic efficiency is probably only valid at maximum thrust, so we need to estimate what the efficiency will be in variable thrust.

As mentioned before, we need to study the relationship between liquid settling time and the acceleration. We also need to find an optimum spin rate. Thermal control is an important issue that needs to be defined. And there is an additional issue about how the whole structure will be deployed and assembled. It seems obvious that the structure will have to be deployed in space. We need to determine the role of robot during the construction and maintenance phase of the life cycle.

And a final nit is the logistics for resupply and refueling. Since the XIPS thrusters will be burning up some fuel, they will need to be re-supplied. These and other details will be the topics of continued study.

Summary

In summary, there are still some outstanding technical issues, but there are no known Physics show stoppers. Liquid mirrors provide excellent figure control ($\lambda/50$) passively. The primary mirror is ultra light-weight, being only 7 kg/m^2. As Newton pointed out, the liquid naturally forms a parabolic surface, which is optimum for telescope optics. No bearings (and therefore there will be induced vibration) required to spin any object in space. Structural supports and dish only need to be manufactured and maintained to 0.1 mm. The liquid mirror has one great advantage over segmented mirrors, they require 4 orders of magnitude less restrictive metrology. In the limit, as the size of the primary gets bigger segmented mirror metrology need to become complex more rapidly than liquid mirror metrology. This advantage will become even more apparent when we strive for larger (> 100 m) space based telescopes.