

In response to Truman Hunter's questions: Analyzing the technical feasibility of using a single interceptor against a single ICBM is the starting point for analyzing the feasibility of a larger system. Analysis of multiple simultaneous threats was beyond the scope of the APS study. The basis for the presumed threats analyzed by the study is described in detail in chapter 3 of the APS report. His other issues lie outside the scope of the study.

## Reference

1. Page and section numbers refer to the published American Physical Society report: D. K. Barton et al., *Rev. Mod. Phys.* **76**, S1 (2004).

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## Mercury Telescopes Highly Reflective, Easy to Clean

Showing that a rotating liquid forms a parabola is an elementary exercise in equations. In optics, one learns that a parabola perfectly focuses a collimated beam of light, which means that the images on axis should be diffraction limited. The derived focal length  $f$  of a rotating liquid turns out to be  $f = g/2(\omega)^2$ , where  $g$  is the acceleration of gravity and  $\omega$  is the angular velocity (radians per second) of the liquid. Mercury is a highly reflecting liquid. Put the concepts together and, in principle, you have a perfect telescope of focal length  $f$ . Robert W. Wood tried it nearly 100 years ago, when he rotated a 50-cm-diameter pan containing mercury:

The instrument resolved stars three seconds of arc apart, showed the small craterlets on the moon, and yielded wonderfully bright images of nebulae when running with a short focus. It was, however, merely a scientific curiosity.<sup>1</sup>

Due to vibrations from the bearing, the room, and the drive belt, Wood's rotating mercury surface had standing waves that affected his images. Much later, rotating curing dishes of epoxies have shown similar

problems.<sup>2</sup> The researchers at Laval University were the first to fabricate a container with a preformed parabolic bottom; the container was rotated on a precision air bearing and had only a 1-mm-thick mercury coating that could not support long-wavelength surface waves. Laval's liquid mirror telescopes (LMTs), 2.5 meters in diameter, have been found to be diffraction limited.<sup>3</sup>

The November 2003 PHYSICS TODAY story (page 24) presents the state of the art for LMTs. Compare, though, the \$1 million 6-meter Hickson LMT to the proposed 30-meter multimirror telescope, which has a projected cost of \$700 million. The apertures of these two telescopes are in the ratio of 1/25, while the costs are 1/700! LMTs have many applications, such as the proposed Large Aperture Mirror Array (LAMA) with a 50-meter effective diameter; that is 3.33 times more aperture than the proposed 30-meter, at 1/14 to 1/7 its cost.

I was involved with the choice and installation of one of the 2.7-meter LMTs mentioned in the story—a lidar collector with a 4.5-meter focal length, located at UCLA's HIPAS ionospheric research facility near Fairbanks, Alaska.<sup>4</sup> First light was 7 May 1995, with parts costing \$45 000. That LMT is in its own two-story structure with an overhead glass skylight, to protect it from local outside winter temperatures of around  $-4^{\circ}\text{C}$ .

The HIPAS LMT has been operating reliably since first light, and has even run for three months continuously on occasion. When the mercury container is first rotated, mercury vapor levels are high; however, with time, the surface oxidizes and the levels are well below the US government safety threshold of  $50\text{ }\mu\text{g}/\text{m}^3$  per 5 hours' exposure. After two weeks of operation, the vapor level is typically  $20\text{ }\mu\text{g}/\text{m}^3$ .

Not mentioned in the article is the ease of cleaning mercury, particularly since all common objects float on it. The container is stopped, and a lead-weighted rubber tube is used to drag debris and mercury oxide to an edge of the puddle, from which the debris is aspirated away. The mirror is then restarted. Because the parabolic mercury reflecting surface is only due to equilibrium between gravity and centrifugal pressures, such easily cleaned mirrors can be used to focus kilojoule laser pulses into the ionosphere for the creation of plasma columns at 100-m altitudes without fear of permanently

damaging the focusing surface.

## References

1. R. W. Wood, *Physical Optics*, 3rd ed., Optical Society of America, Washington, DC (1988), p. 49.
2. Y. Ninomiya, *Appl. Opt.* **18**, 1835 (1979).
3. L. Girard, E. F. Borra, *Appl. Opt.* **36**, 6278 (1997).
4. Y. Wong et al., *Radio Science* **25**, 1269 (1990).

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## Pre-Kepler Mathematical Descriptions of the Heavens

In a book review in the December 2003 issue of PHYSICS TODAY (page 61), Gale E. Christianson states that Johannes Kepler was "the formulator of the first mathematical laws of the heavens." Actually, although Kepler gave an excellent description with his three laws, other mathematical theories of planetary motion had been given previously, going back to antiquity. One could make a good case that the first mathematical description of the heavens predates Claudius Ptolemy, going back to Eudoxus and his theory of uniform motions on concentric spheres (around 370 BC), or even earlier.<sup>1</sup>

The most successful and most mathematically sophisticated planetary-motion theory was from Ptolemy in the second century AD. He gave a surprisingly accurate method for computing the positions of the five then-known planets and our moon. His lunar theory also gave good predictions concerning parallax, the size of the Moon and its distance from Earth, and lunar eclipses. The Ptolemaic system had Earth as its center point and based all motion on circles, but by use of epicycles and eccentric circular motion, it achieved great accuracy.<sup>2</sup> In that regard, it was not superseded until Kepler's work in the 17th century.

Another mathematically sophisticated formulation that preceded Kepler was the Copernican theory, from the 1540s. Although Copernicus had the Sun as the center point, he still used circular motion, and made greater use of epicycles than did Ptolemy.<sup>3</sup>

## References

1. O. Neugebauer, *The Exact Sciences in Antiquity*, 2nd ed., Dover, New York (1969).