cloud cover would imply a shorter launch-delay time, it is essential to tighten the 7-km estimate before making such certain conclusions. Estimates should also be made on a more careful regional basis—a general mid-latitudes average might differ significantly from a specific estimate for Iran or North Korea.

Even if one were to accept the article authors' basic technical analysis, there is still reason to question how they translate it into judgments about North Korea and Iran. Consider the authors' first conclusion on North Korea: "Using terrestrial-based interceptor rockets to defend the 50 states against liquid-propellant ICBMs [intercontinental ballistic missiles] launched from North Korea may be feasible, but that would push the limits of what is possible physically, technically, and operationally." Presumably, that statement refers to the 10-km/s I-5 interceptor, since only that interceptor is characterized in the article as "a surface-based interceptor with a performance at the limit of what might be practical." Yet the study refutes their conclusion—twice! In its executive summary, the study states that defending against North Korea "would require interceptors with speeds of 6.5 km/s"—those would be the less capable I-4, not the envelope-pushing I-5. And further on, in the detailed discussion of North Korea, the study says "To defend [the US], the 5-km/s interceptor would have to be fired with zero decision time." That the study authors offer no technical reason to reject the zero-decision-time option presumably implies that even the rudimentary 5-km/s I-2 interceptor could do the job.

The article authors assert, "Taking all relevant factors into account, . . . we reached the conclusion that defending the 50 states against solid-propellant ICBMs, from either North Korea or Iran, would not be feasible." But again, the study refutes this claim. Regarding North Korea, a statement on page 124 says, "Even the 6.5-km/s interceptor could be used to defend" the US. And farther down that same page, "The giant 10-km/s interceptor . . . could be used with about 30 s of decision time." Neither statement agrees with the article's conclusion that no defense is feasible.

The article's pessimism with respect to solid-propellant ICBMs isn't justified for Iran, either. According to the APS study, "It appears that by basing a 10-km/s interceptor in the Caspian Sea and a second one in Afghanistan or Turkmenistan, all 50 states could be defended" (page 94) against missiles launched from central Iran. However, the study further states, "If the launching site for solid-propellant missiles destined for [Washington, DC] . . . were moved about 200 km to the southeast, this defense would be precluded." That statement is transparently incorrect. If one extrapolates from the study's figure 5.17, the base in western Afghanistan would clearly be able to intercept effectively. Thus, the study should not be read as implying that defense against Iran is impossible.

These are technical, rather than political, reasons to question the study's overall pessimism. Still, because the study contains some optimistic assumptions that might yet be tightened, even a revised version would not necessarily conclude that boost-phase defense is possible. These persistent ambiguities warrant further study.

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The article about the APS study on boost-phase missile defense gave considerable information on the physical challenges of such defense. However, many more questions need to be asked and answered.

It may technically be possible to build a system to stop one missile, but how about 5, 10, or more? Where will those missiles be coming from? Who is going to have such missiles in quantity?

Can anyone guarantee that *all* incoming missiles will be stopped? What will such a total system cost? Are the potential lives and property saved worth that cost?

This and other space-based projects, many of which later turn out to be boondoggles, are supported by NASA, the military, and industries looking to generate job protection and company profits for years to come. The proposed manned trip to Mars, the permanent base on the Moon, the orbiting space lab now under construction, robots exploring the Mars surface, are or will be a waste of money. If water existed on Mars millions of years ago, what relevance has that to us on Earth today, or even in the distant future?

I think the excessive costs of space projects versus their minimal value gained needs a very careful reevaluation. I believe that very little has been gained from research in space; most of the benefits have been from research on the ground *for* the space program. Exceptions include satellites for weather, communication, Earth mapping, astronomy, and military information.

Congress will not stop spending on wasteful projects. The members get too much election campaign money from lobbyists. Citizens with some technical knowledge and common sense need to get together and demand a change in the funding of these projects, with members of the physics community taking a lead role. There are far better places than space to spend money for research, development, and education.

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Kleppner, Lamb, and Mosher reply: The APS study concluded that a boost-phase defense using airborne interceptors (ABIs) incorporating technology that would be available within the 10-year period considered could be useful in limited circumstances. Dean Wilkening's analysis agrees with the study's in most respects, but his assessment of the utility of ABIs is more positive.

One reason the assessments differ is that Wilkening assumes an airborne X-band radar system will be available. No such system yet exists. The study judged that the time required to field such a system would be greater than the 10-year period considered. A second reason is that his interceptor has a higher acceleration than the study's comparable interceptor I-2 and has a 20-second burn time compared to the 40-s burn time of I-2. Because Wilkening's interceptor has a higher average velocity, it can reach a greater distance, but there are penalties for such a high acceleration. Wilkening's analysis appears to neglect one of these: The interceptor's final stage (kill vehicle) must have more velocity change ("divert") capability because it is released after only 20 s, when it has less information about the intercontinental ballistic missile's flight and must maneuver for a longer time. Wilkening's kill vehicle has a total divert capability of 2 km/s, which is what the study estimated would be required for a kill vehicle released after 40 s. Additional divert capability increases the mass of the kill vehicle and its boosters and reduces the final speed of the interceptor that a given aircraft can carry.

Wilkening says existing US and Russian solid-propellant ICBMs have nominal burn times of 180 s, whereas the computer models constructed by the study have 170-s burn times. But a 10-s increase in burn time would increase the I-2's ground range by only 40 km, negligible compared to the other uncertainties. Although one must pick specific numbers for any analysis, no countries of concern currently have ICBMs, so the characteristics of missiles they might use are unknown.

Richard Garwin raises three principal issues. In his reference 1, second document, he says "there should be no tactical human decision" and therefore the decision time introduced in the APS report is not needed. Decision time, as defined in the report (page xxiii),[1] refers to the additional time the defense might require for the system to be effective—for example, to communicate between different elements or to estimate better the characteristics of the threatening rocket. No human decision is necessarily implied. The zero-decision-time timeline in the report is a bounding case: Interceptors could not be fired earlier, even if the many optimistic assumptions built into the analysis—including detailed advance knowledge of the attacking ICBM's performance characteristics, a planar ICBM trajectory, no issues of battle management, communications, command, reliability, and so forth—were satisfied and the system worked perfectly. A practical defense must allow for these factors by basing interceptors closer to the intercept point or using faster ones. Such a margin can be characterized by a time. We chose to illustrate the effects of those margins by showing the effect of a 30-s margin. Building a system with no margin would be unwise.

Garwin argues that radar 400 km from the ICBM launch site could provide the missile warning and tracking information required to fire interceptors and could add tens of seconds to the time available for intercept. The study found that ground- or sea-based radars could provide this information, but would increase the intercept time provided by the advanced space-based detection and tracking system considered in the study only if radars are stationed less than 300 km from all potential ICBM launch sites. However, that would require stationing radars in enemy territory or within 100 km of an enemy coastline, contrary to the study's guidelines. The study found that if the defense had to rely on the existing Defense Support Program (DSP) system, ground-based radars could improve midcourse guidance of interceptors.

Garwin calls attention to the usefulness of a 14-ton (12.7-tonne), 8.5-km/s, 100-s burn time interceptor for defending against a liquid-propellant ICBM launched from North Korea to the continental US. An 8-km/s interceptor was discussed in section 5.1.2 of the study. If it has a burn time of 40–45 s, its range can be estimated by interpolating between those of the study's 6.5- and 10-km/s interceptors. Such an interceptor would be more manageable than a 10-km/s one. The study found that the average velocities of 6.5- to 10-km/s interceptors with burn times longer than 40–45 s were generally too low to be effective. Interpolating between the results for 6.5- and 10-km/s interceptors, we estimate that Garwin's suggested 8.5-km/s

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interceptor with a burn time of 100 seconds would have an effective range several hundred kilometers less than with a 40-s burn time.

Michael Levi's proposal to launch enough interceptors to cover all potential ICBM trajectories the moment a possible missile launch is detected raises serious technical, operational, and policy issues that, as far as we know, have not been analyzed. The most serious is the false alarm problem, which would be greatly exacerbated. Space-based IR missile warning and tracking systems must contend with an extremely cluttered environment. It takes time to observe a target long enough to establish that it is an ICBM and not sunglint from clouds and ice, a fighter aircraft using its afterburner, a fire, or a short-range missile. Radars also must wait for an ICBM to accelerate and pitch over to separate its return signal from background clutter and rightly identify it.

Firing a fusillade of interceptors as soon as a possible missile launch is "detected" would cause frequent false-alarm launches, waste dozens of interceptors, and make it possible for the attacker to exhaust the defensive system's supply of interceptors by, for example, launching shorter-range missiles or other decoys before or while launching ICBMs. In addition to the very large number of interceptors required, the system would have to be able to eliminate the interference with its sensors and the possible fratricide caused by having such a large number of interceptors in flight.

Levi mentions cloud coverage. The study considered separately the available data on the altitude and optical depth distributions of cloud cover over land, sea, and coastal areas as a function of latitude (see section 10.1). To avoid ground clutter, the DSP missile detection and tracking system is designed to detect only IR sources above 10 km. The study also considered a modern, see-to-the-ground missile detection and tracking system. Although cloud tops can extend to 10 km, their average height over land is 4.7 km. An enemy has no obligation to attack only when the weather is clear. At low altitudes, ICBMs would not have sufficient ground speed for the defense to separate them reliably from the background. After considering these and other factors, the study concluded that clouds above 7 km are sufficiently rare that a modern system could reliably detect rockets by the time they reached that altitude, but not at significantly lower altitudes.

Contrary to Levi's assertion, the 6.5-km/s interceptor would indeed "push the limits of what is possible." The challenge is not in interceptor speed, but in meeting the total system requirements. Earlier in this piece, we mentioned some of the challenges. Others include solving the "plume-to-hardbody handover" problem, and development and testing of the sensors and the guidance and control algorithms needed for the kill vehicle to hit an unpredictably accelerating target. The 5-km/s interceptor Levi mentions could succeed only under perfect circumstances, and such a scenario is implausible.

Levi attributes to the three of us the quotation concerning the difficulty of defending all 50 states against solid-propellant ICBMs; however, that is the conclusion of the entire study group (page xxii), which also concluded that "when all factors are considered none of the boost-phase defense concepts studied is likely to be viable for the foreseeable future to defend the 50 states against even first-generation solid-propellant ICBMs" (page xxxvii).

The quotation Levi recites on using the 6.5-km/s interceptor to defend against North Korea is incomplete. In full, it is "The lower-left panel of Figure 5.10 reveals that even the 6.5-km/s interceptor could be used to defend Boston *only if it were fired very close to the coast with zero decision time*." The restored words, shown here in italic, reverse the meaning. The study concluded that defense of the US against solid-propellant ICBMs, even with a 10-km/s interceptor, is "unlikely to be practical when all factors are considered" (page xxii) because such a defense would be at the limit of what is physically possible and the system would not have enough margin to be robust in the likely event of less than ideal circumstances.

Levi also refers to the study's discussion of defending against solid-propellant ICBMs from Iran by basing 10-km/s interceptors near Iran's coast in the Caspian Sea. The study called such basing locations "unconventional" and regarded them as implausible because of operational, security, and policy concerns. We disagree with Levi's conclusion that an interceptor base in western Afghanistan would be useful.

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 ω 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.[1]

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.[2] 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.[3]

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.[4] 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°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 μg/m^3 per 5 hours' exposure. After two weeks of operation, the vapor level is typically 20 μg/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.

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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.[1]

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.[2] 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.[3]

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