Research Highlights

The X-Ray Laser From Underground to Tabletop

Figure 1. Jim Dunn makes adjustments to the tabletop x-ray laser's target chamber.

THE concept for x-ray lasers goes back to the 1970s, when physicists realized that laser beams amplified with ions would have much higher energies than beams amplified using gases. Nuclear explosions were even envisioned as a power supply for these high-energy lasers. That vision became a reality at the time of the Strategic Defense Initiative of the 1980s, when x-ray laser beams initiated by nuclear explosives were generated underground at the Nevada Test Site. Livermore's Novette, the precursor of the Nova laser, was used for the first laboratory demonstration of an x-ray laser in 1984.

Since then, Nova, Livermore's largest laser, has set the standard for x-ray laser research and been the benchmark against which x-ray laser research has been measured. Nova uses a very-high-energy pulse of light about a nanosecond (a billionth of a second) long to cause lasing at x-ray frequencies. Because these high-energy pulses heat the system's glass amplifiers, Nova must be allowed to cool between shots. Nova can thus be fired only about six times a day.

In contrast, a team at Livermore has developed a small "tabletop" x-ray laser that can be fired every three or four minutes. By using two pulses—one of about a nanosecond and another in the trillionth-of-a-second (picosecond) range—their laser uses far less energy and does not require the cooling-off period.

Scientists had theorized for years that an x-ray laser beam could be created using an extremely short, picosecond pulse, which would require less energy. But very short pulses overheated the glass amplifiers, destroying them. Laser chirped-pulse amplification, developed in the late 1980s, gets around that problem by expanding a very short pulse before it travels through the amplifiers and then compressing it to its original duration before the laser beam is focused on a target.[1] If chirped-pulse amplification is combined with lower energies, the pulses do not overheat the glass amplifiers, so the system can be fired many times a day.

The development team for this new laser includes Jim Dunn, the experimentalist, and theoreticians Al Osterheld and Slava Shlyaptsev, a visiting scientist from Russia's Lebedev Institute. All are physicists in the Physics and Space Technology Directorate. Together, they have produced one of only a handful of tabletop x-ray lasers in the world (Figure 1).

X-ray lasers produce "soft" x rays, which is to say their wavelengths are a bit longer than those used in medical x rays. Soft x rays cannot penetrate a piece of paper, but they are ideal for probing and imaging high-energy-density ionized gases, known as plasmas. X-ray lasers are an invaluable tool for studying the expansion of high-density plasmas, particularly laser-produced plasmas, making them useful for Livermore's fusion and physics programs. Basic research using x-ray lasers as a diagnostic tool can fine-tune the equations of state of a variety of materials, including those used in nuclear weapons and under investigation by the Stockpile Stewardship Program. These lasers also have applications for the materials science community, both inside and outside the Laboratory, by supplying detailed information about the atomic structure of new and existing materials.

Notes Osterheld, "Plasmas do not behave nicely. To verify the modeling codes for plasmas, we need lots of experiments." With an experiment every three or four minutes on the tabletop x-ray laser, large quantities of data can be produced quickly. The team's goal is to refine the process and reduce the size and cost of the equipment so that someday an x-ray laser might be a routine piece of equipment in plasma physics research laboratories.

Achieving a Stable Lasing Plasma

In x-ray lasers, a pulse of light strikes a target, stripping its atoms of electrons to form ions and pumping energy into the ions ("exciting" or "amplifying" them). As each excited ion decays from the higher energy state, it emits a photon. Many millions of these photons at the same wavelength, amplified in step, create the x-ray laser beam. The highly ionized material in which excitation occurs is a plasma (which should not be confused with the plasma that the x-ray laser beam is later used to probe).

X-ray lasers are specifically designed to produce a lasing plasma with as high a fraction of usable ions as possible to maximize the stability and hence the output energy of the laser. If the target is made of titanium, which has 22 electrons, the ionization process strips off 12 electrons, leaving 10, which makes the ions like a neon atom in electron configuration. Neonlike ions in a plasma are very stable, closed-shell ions. They maintain their stability even when faced with temporal, spatial, and other changes. Dunn, Osterheld, and Shlyaptsev have also studied palladium targets. When palladium atoms are stripped of 18 electrons, their ions become like a nickel atom, which is also closed-shell and stable.

A One-Two Punch

In Livermore's Nova laser, a high-energy, kilojoule pulse lasting a nanosecond or slightly less must accomplish three things: produce an initial line-focus plasma, ionize it, and excite the ions. Because the excitation, or heating, is happening relatively slowly compared to other plasma behavior, this process is called quasi-steady-state excitation.

The tabletop x-ray laser is configured differently from Nova (Figure 2). It uses the compact multipulse terawatt (COMET) laser driver to produce two pulses. First, a low-energy, nanosecond pulse of only 5 joules strikes a polished palladium or titanium target to produce the plasma and ionize it. The pulse must accomplish less than the Nova pulse, so less energy is needed.

Then a 5-joule, picosecond pulse, created by chirped-pulse amplification, arrives at the target a split second later to excite the ions. Although the picosecond pulse uses 100 times less energy than a Nova pulse, its power is ten times higher

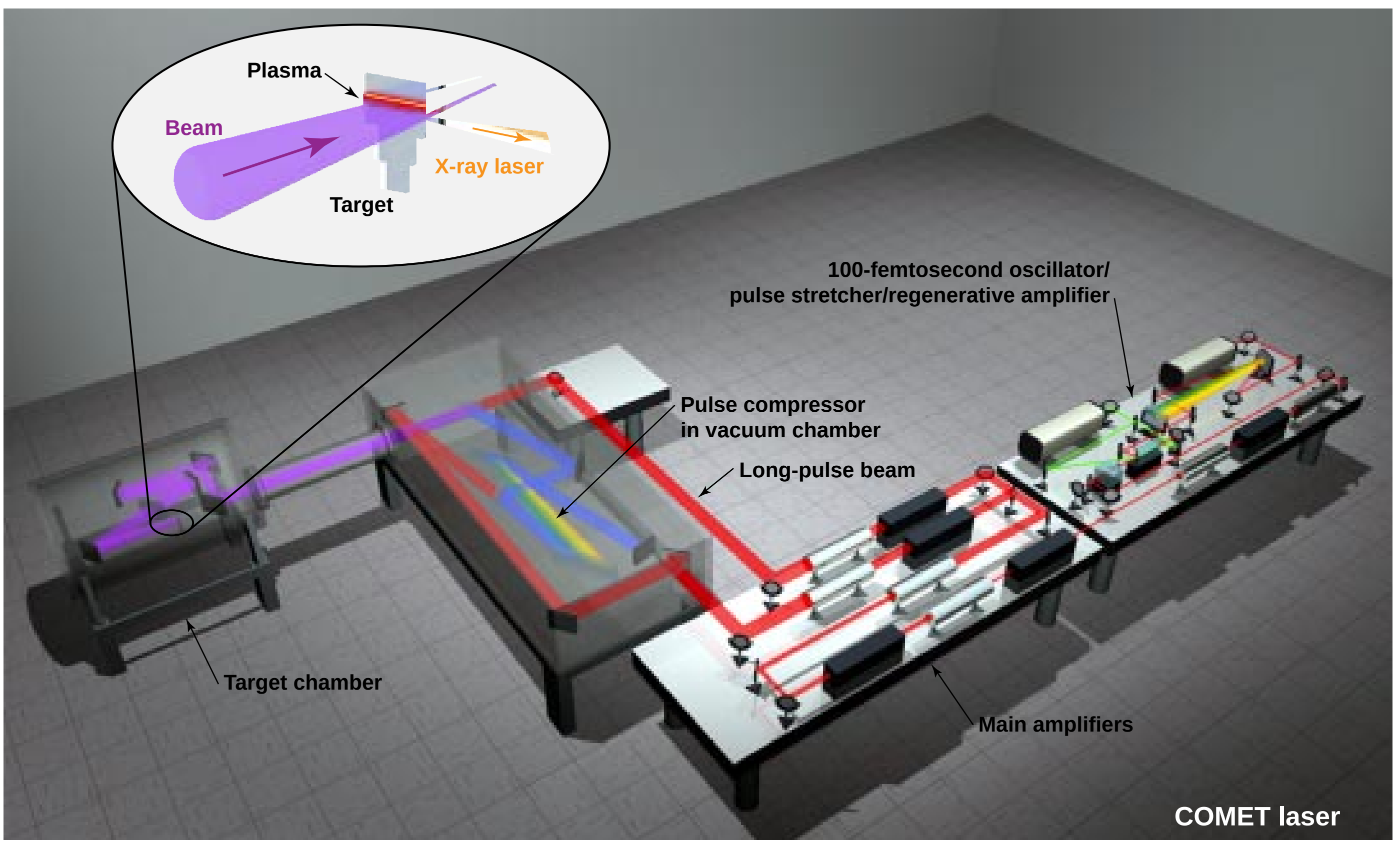

Figure 2. Rendering of Livermore's COMET (compact multipulse terawatt) tabletop x-ray laser showing the laser system and target chamber. The inset shows laser beams hitting the stepped target and producing a plasma, which in turn generates an x-ray laser beam.

because the pulse is one thousand times shorter. And its power density, which adds the length of the target to the power equation, is also very high.

The brief, picosecond, "transient" plasma excitation plays a major role in the laser's effectiveness. During the ionization process, the plasma expands rapidly. In the quasi-steady-state approach used with Nova, excitation occurs while the plasma is continuing to expand and be heated so that much of the deposited energy is lost from the lasing process. With the transient scheme, excitation happens so fast that more ions in the plasma can contribute to the lasing.

For plasma research purposes, the tabletop x-ray laser almost has it all—low energy requirements, high power, a repetition rate of a shot every four minutes, and a short wavelength. (Keep in mind that the shorter the wavelength of the laser, the more effectively it can penetrate high-density plasmas.)

Two Plasmas in One Chamber

To date, the Livermore team has studied neonlike titanium and nickel-like palladium transient schemes. It has produced the first transient-gain, nickel-like, x-ray lasing at 14.7 nanometers with a laser pump of less than 10 joules (Figure 3).[2] The team is looking at various ways to maximize the laser's output, including using different target designs and delaying the arrival of the picosecond pulse to match the propagation of the x-ray laser in the gain region.

Within the next year, the team plans to have a second plasma in the target chamber. The first one will be for lasing, while the second will be studied and probed. The very-short-pulse x-ray laser probe will act as a strobe to "freeze" the action of the second plasma, resulting in clearer images of plasmas than any yet produced. And with an experiment every three or four minutes, there can be lots of excellent images.

—Katie Walter

Key Words: chirped-pulse amplification, plasmas, soft x rays, tabletop x-ray laser.

References

1. For more information on chirped-pulse amplification, see *Science & Technology Review*, "Crossing the Petawatt Threshold," December 1996, pp. 4–11.
2. J. Dunn, A. L. Osterheld, R. Shepherd, W. E. White, V. N. Shlyaptsev, and R. E. Stewart, "Demonstration of X-Ray Amplification in Transient Gain Nickel-like Palladium Scheme," *Physical Review Letters* **80**(13), 2825–2828 (1998).

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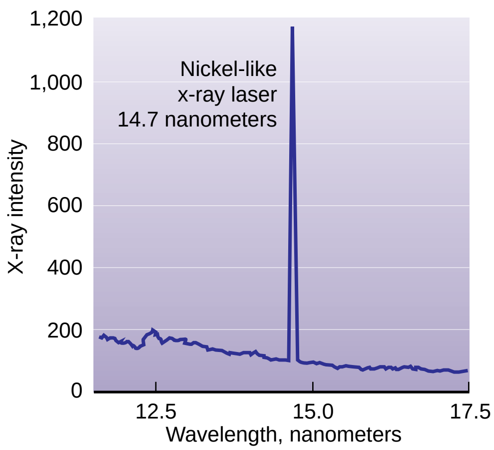


Figure 3. A line out of the emission spectrum from an x-ray laser experiment shows that the 14.7-nanometer x-ray laser line is orders of magnitude brighter than any other emission line.

Down-to-Earth Testing of Microsatellites

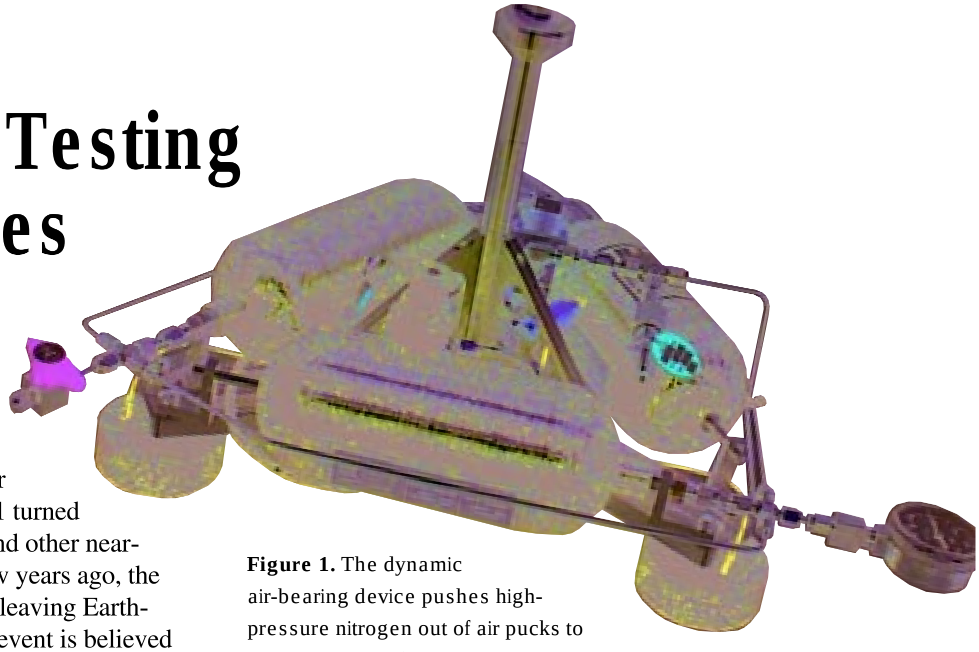


Figure 1. The dynamic air-bearing device pushes high-pressure nitrogen out of air pucks to create a gravity-free environment in which space vehicles can maneuver with five degrees of freedom.

ALTHOUGH the recent prediction of a near collision between Earth and asteroid XF11 turned out to be inaccurate, hazards from asteroids and other near-Earth objects are out there. After all, just a few years ago, the Shoemaker–Levy comet hurtled onto Jupiter, leaving Earth-sized scars on the planet's face, and a similar event is believed to have caused the extinction of the dinosaurs on Earth. The few nervous moments we Earthlings had over XF11 serve as a reality check on the hazards that await from space.

Scientists and engineers at Lawrence Livermore have been engineering small, agile satellites that can help deal with potential space calamities. Called microsatellites (microsats, for short), they are an outgrowth of research performed for the Laboratory's Clementine satellite program, which mapped the moon and then discovered the first evidence that water may exist there. The microsatellites are envisioned as operating autonomously in orbit to serve a variety of future space-exploration needs in addition to probing near-Earth asteroids. Microsatellites would be able to strike or probe the potentially hazardous objects that threaten Earth. In addition, they might be handy rescue vehicles used to inspect disabled satellites and relay observations about them to ground stations; they might also dock with and repair satellites. Microsatellites could also be part of a control system that protects and defends U.S. assets in space.

The capability for such uses will come through integrating a complex array of advanced technologies in the microsatellite vehicle. Sensors, guidance and navigation controls, avionics, and power and propulsion systems—all must perform precisely and in concert so the vehicles can find, track, lock onto, and rendezvous with their targets, even though those targets are also on the move. The rigorous ground testing of microsatellites' integrated technologies is essential; these tests produce data needed for effective flight testing.

The best ground-testing environment is one that mimics, as much as possible, the free-floating environment of a space flight. Finding a way to emulate such an environment was one of the important tasks facing microsatellite developers.

Inspired by a Game

Traditionally, space vehicles have been ground tested on a stationary hemispherical air bearing, a device that floats a test vehicle with high-pressure air. The air bearing provides the vehicle with three angular degrees of freedom. The stationary air bearing is useful for testing the stability of a space vehicle in orbit. But because microsats will be performing precision maneuvers in space that involve translation—that is, parallel, sideways motions—its testing must also account for linear dynamics.

Clementine II program leader Arno Ledebuhr, engineering group leader Larry Ng, and mechanical engineers Jeff Robinson and Bill Taylor came up with the idea for a dynamic air-bearing device that provides five degrees of freedom (three rotational, or angular, and two translational, or linear, motions). Their inspiration came from the game of air hockey, which uses air pushed out of a table to float hockey pucks. In the dynamic air bearing, this configuration is inverted—the air is pushed out of the pucks. Three such air pucks are used to support a traditional air bearing on a fixture that also includes an air supply—from high-pressure nitrogen tanks (Figure 1). As the air pucks release the high-pressure air, the whole device is lifted off the surface on which it has been sitting. Because the three air pucks, equally distributed on a 19-centimeter-radius circle, can support a total weight of more than 150 kilograms, it capably floats itself (5 kilograms) and a microsat test vehicle (25 kilograms). It thus allows the test vehicle to move linearly as if in a near-zero-gravity space environment.

Scaling Down Space Maneuvers

The Livermore team is using the dynamic air-bearing device in a series of experiments called AGILE, for air-table guided-intercept and line-of-sight experiments. These experiments will evaluate a vehicle's ability to "divert," that is, maneuver in space while keeping track of a moving target (such as an incoming asteroid) and then close in to intercept it. The objective of these experiments is to quantify the distances by which the microsats miss intercepting the target, thus allowing microsat developers to identify hardware and software deficiencies.

For a vehicle to accomplish an interception, its sensors and measurement, navigation, and control systems must work together to continually calculate vehicle speed and position in relation to the target. They must calculate the point at which the target can be intercepted and get the vehicle to that point at precisely the same time as the target. Because both the vehicle and target are moving, the line of sight to the target continually changes, and therefore, vehicle acceleration and position must be constantly adjusted. Further complicating these calculations are the many other factors that can affect maneuvering precision, such as changing vehicle mass due to fuel expenditure, vehicle acceleration capability, and minor misalignment of hardware components.

The interception experiments use a test vehicle that can move with five degrees of freedom. The vehicle sits on the dynamic air bearing, which in turn is borne on two large, smooth glass plates resting side by side on a table. The glass plates form a rectangular test table approximately 1.5 by 7.2 meters. A laser projects a target onto a wall-mounted target board parallel to the long side of the glass test table. A precision measurement system, consisting of a laser and a camera, accurately measures and records the test vehicle's position (Figure 2).

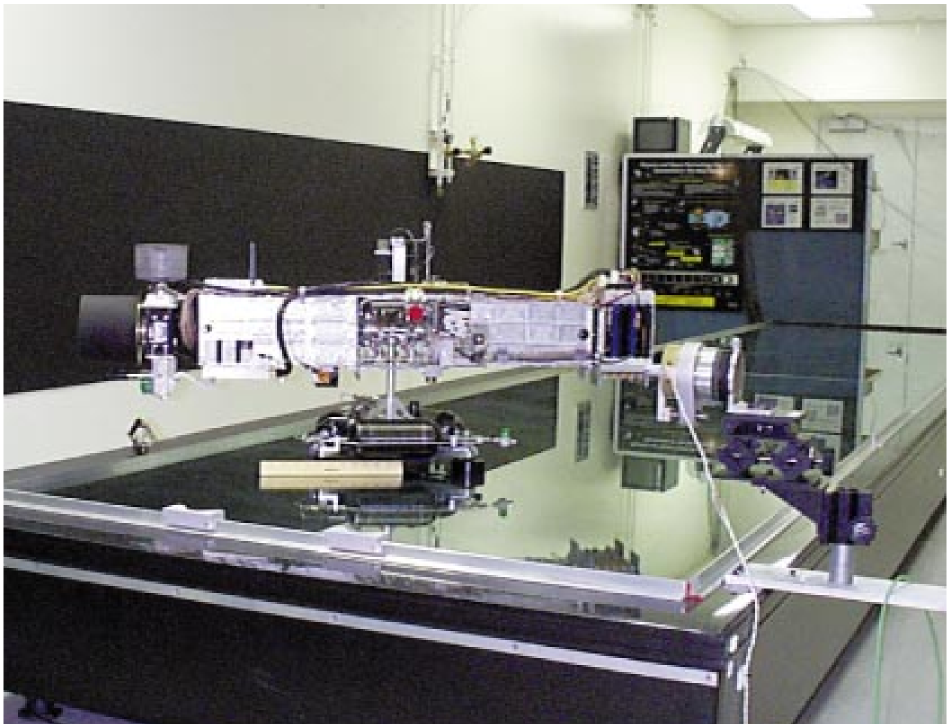


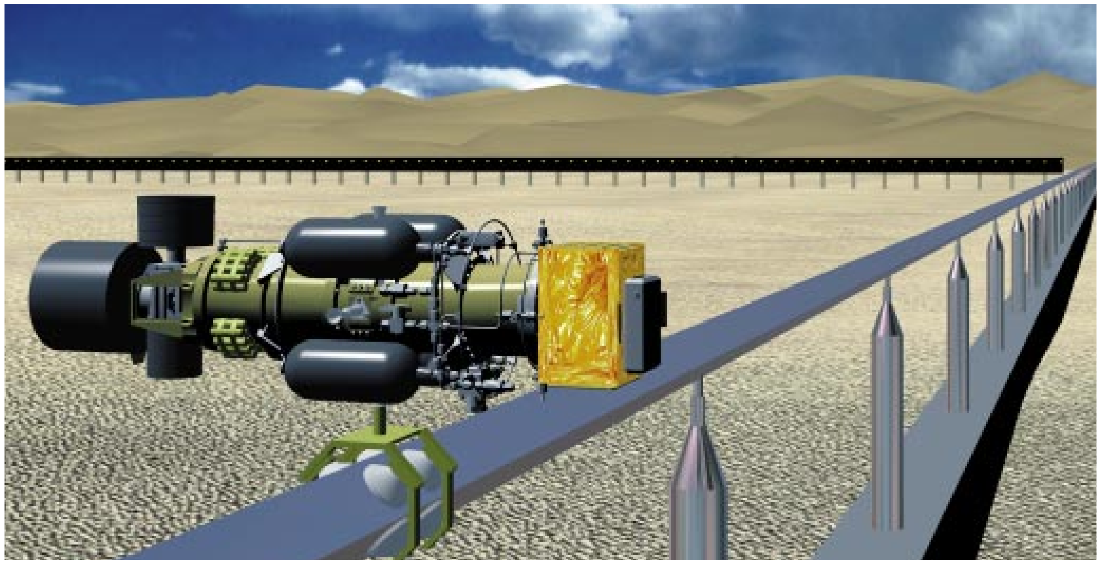
Figure 2. The dynamic air-bearing device floats a microsatellite above a glass surface to test the microsatellite's ability to accurately track and maneuver to its target.

The intercept geometry, comprising the vehicle positions, target positions, and the changing line of sight between them, is scaled for the indoor table experiment to preserve the intercept geometry of an actual flight. For example, for a successful interception, the line-of-sight rate must approach zero; that is, the vehicle and target must both arrive at the same point at the same time. To preserve that line-of-sight requirement in the test, the test maneuvering distance is scaled down in relation to the target that is projected on the screen. The target location and interception point are predetermined, and these values, used in conjunction with the precise measurements of vehicle position (from the laser measurement system), allow experimenters to determine the ability of the onboard guidance and control software to maneuver the vehicle to the point of interception.

Taking Testing to the Next Steps

The current rectangular, indoor dynamic air-bearing test setup is useful for a variety of experiments. However, the short length of the current glass test surface limits maneuvering distance, thus prohibiting replication of the exact

Figure 3. To improve replication of flight maneuvers and provide more accurate tracking of vehicle position, Livermore scientists are designing a large, outdoor version of the dynamic air bearing. The larger scale means more precise reconstruction of line-of-sight angles, which in turn means improved predictions of how to maneuver the test vehicle to meet with its target.



frequency and duration of engine acceleration in actual flight maneuvers. Making the test surface larger and square (10 meters by 10 meters) will enable the performance of a greater range of rendezvous and docking maneuvers, including practicing the circumnavigation of a satellite and determining its spin axis and rotation rate.

To eliminate some of the indoor setup's limitations, an outdoor version of the device is being developed. In this version, the test vehicle "floats" on a smooth rail 100 to 200 meters long and "views" a tilted board on which an incoming target is projected (Figure 3). The rail air-bearing system can move in only one linear direction, but because of its larger scale, it provides an improved replication of flight maneuvers and a more accurate tracking of vehicle position. Both improvements lead to a more precise reconstruction of line-of-sight angles, which is key to correctly predicting the point at which the microsat maneuvers to its target.

The air-bearing team's work on ground testing techniques continues. To date, a 17-meter-long rail has been used to "fly" the newest generation of the microsat vehicle. Longer range outdoor docking experiments that incorporate both an onboard Star Tracker camera, which uses stars to calculate the orientation of the microsats, and a global positioning system receiver are in the planning stages.

—Gloria Wilt

Key Words: AGILE (air-table guided-intercept and line-of-sight experiments), dynamic air-bearing table, dynamic air-bearing rail, ground testing, microsat, microsatellite, spacecraft interceptor, space vehicle.

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