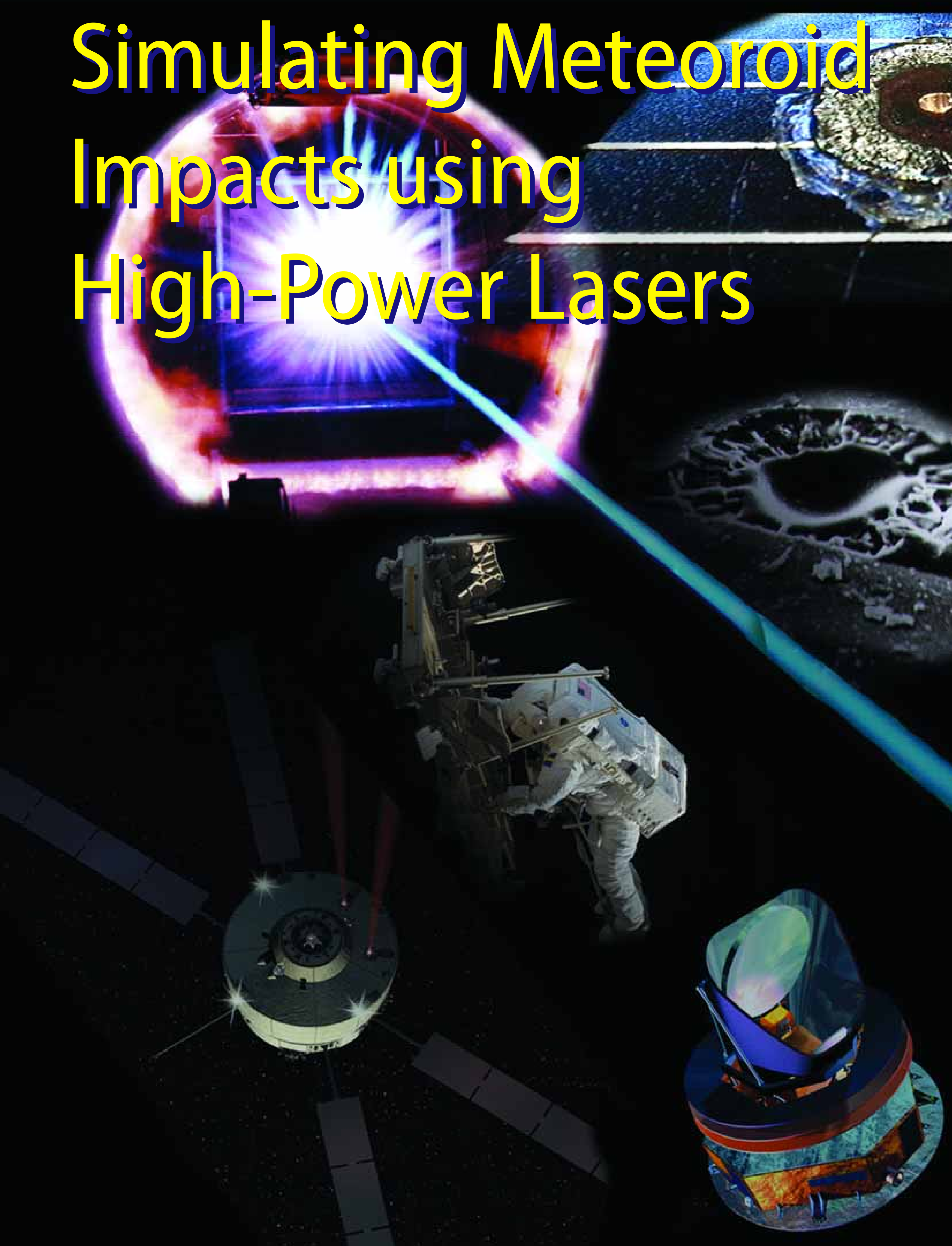
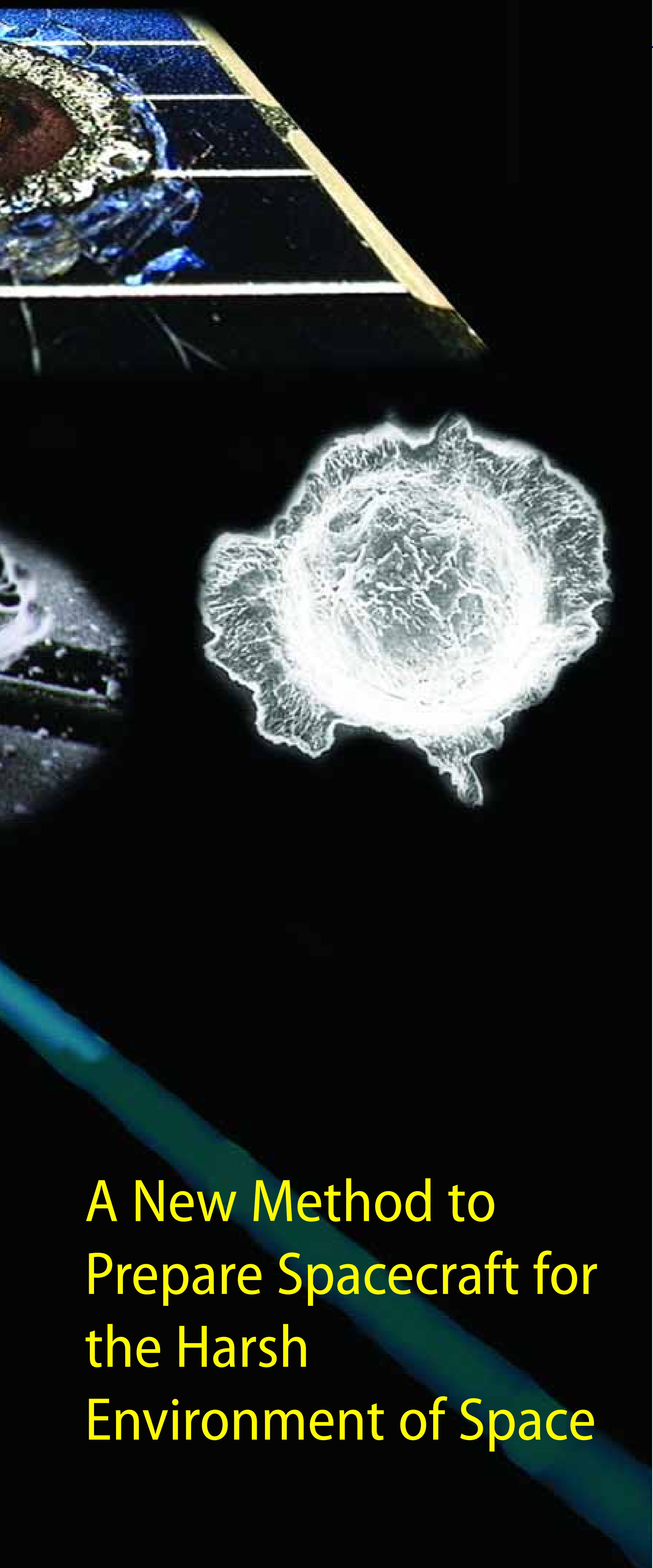
Simulating Meteoroid Impacts using High-Power Lasers





A New Method to Prepare Spacecraft for the Harsh Environment of Space

Markus Landgraf
Mission Analysis Section, Flight Dynamics Division, Directorate for Operations & Infrastructure, ESOC, Darmstadt, Germany

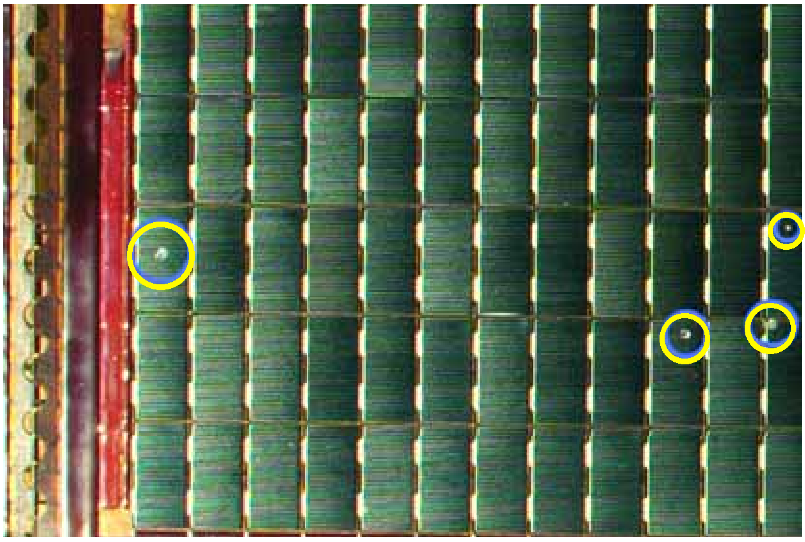
Gerhard Drolshagen
Space Environments & Effects Analysis Section, Directorate of Technical & Quality Management, ESTEC, Noordwijk, The Netherlands

Zoltan Sternovsky, Scott Knappmiller & Mihály Horányi
Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, USA

Meteoroids are one of the most damaging elements in space: at 20 km/s even one the size of a grain of salt can wreak the same damage as a cannonball fired at 1000 km/h. The solar wings of the Hubble Space Telescope returned from space are peppered with holes and craters from meteoroids and space debris. Satellites must be protected from such impacts through careful design and testing. In laboratory testing, firing a high-power laser at a satellite hull efficiently simulates all aspects of the impact: the cratering, the shock travelling through the material, and the impact cloud that can knock out electronics. It can also be used to calibrate detectors that characterise the meteoroid and debris environment, allowing sensitive instruments to be protected simply by carefully choosing a satellite's orientation.

Introduction

Hardware brought back from orbit bears the marks of meteoroid bombardment. ESA's Eureca retrievable carrier was returned from space by the Space Shuttle in 1993 after 10 months in low Earth orbit and showed numerous craters (*Bulletin* 80; *http://www.esa.int/*



Electron-microscope image of a crater in a Space Shuttle window. (NASA/JSC)

Left: a 26 x 13 cm piece of solar panel from the Hubble Space Telescope after more than 8 years in space. Only the larger craters are marked

esapub/bulletin/bullet80/ace80.htm). From Eureca and three sets of solar cells retrieved from the Hubble Space Telescope (HST) we know that meteoroid impacts cause structural damage as well as surface degradation. The craters are normally 10–20 times larger than the meteoroid itself. So, even a millimetre-sized particle can destroy structural elements or penetrate a pressure vessel such as a tank or a crew module. Careful design of the spacecraft structure – perhaps using meteoroid shields – must ensure that impacts are without serious consequences. For example, ESA's Columbus module and Automated Transfer Vehicle are protected by 'Whipple-shields', which fragment any impactor smaller than 1 cm before it can penetrate the hull.

Besides structural damage, which requires relatively large meteoroids, another effect is the continuous degradation of exposed surfaces. Optical surfaces like camera lenses are most sensitive to the large number of submillimetre craters that accumulate over time.

There are also more subtle, indirect consequences. The highly energetic impact creates a small cloud of electrically charged material that can disturb electrical systems onboard a satellite. For example, the loss of solar cells on HST has been linked to a discharge avalanche that could have been started by a meteoroid impact.

Satellites that must maintain very stable positions in space are also affected by meteoroid impacts. Subsatellites in interferometer astronomy constellations, such as ESA's proposed Darwin and XEUS, have to control their separations with other members of the formation to within a few millimetres. In these cases, a meteoroid could break the optical connection.

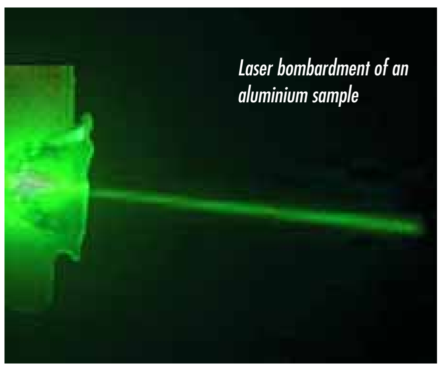
This list of effects shows that, while our current understanding of meteoroids certainly allows us to prepare missions for the space environment, it is imperative that we improve our understanding of the meteoroid environment and expand the Agency's testing capabilities to handle the more sophisticated and sensitive equipment of the future.

Classic Meteoroid Testing Methods

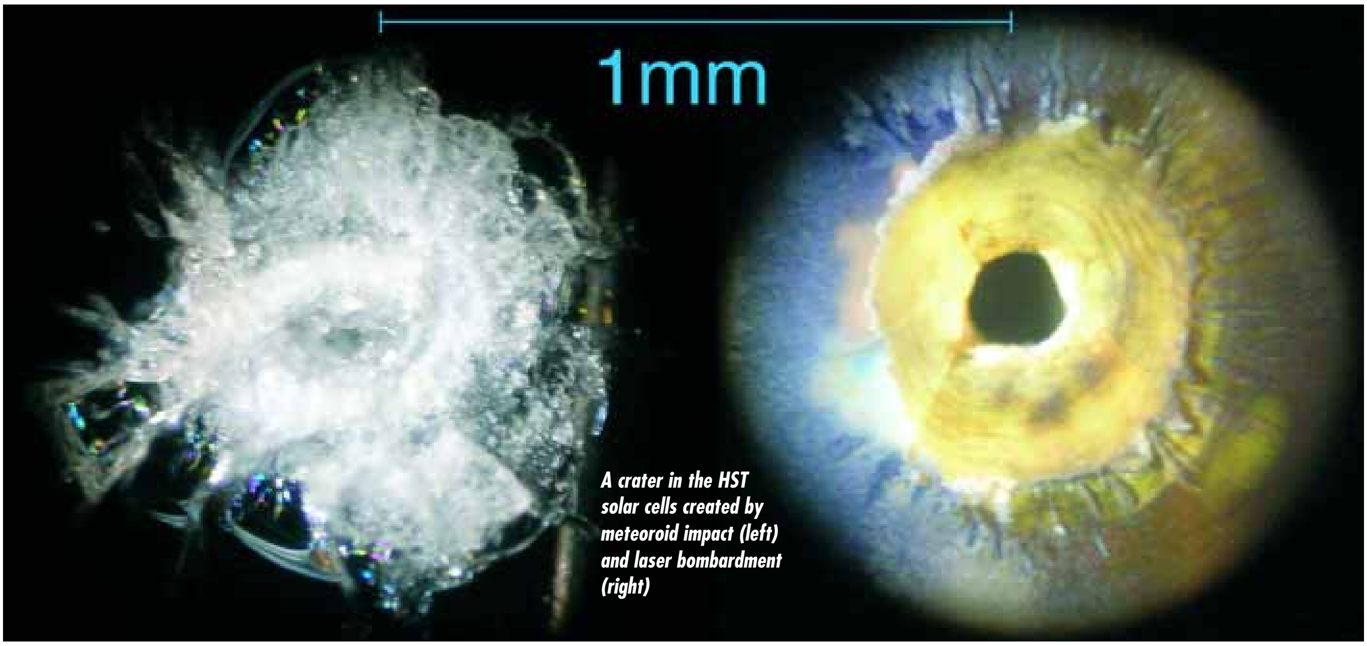
Recreating a meteoroid impact to test space materials in the laboratory requires a solid particle to be accelerated to the extreme speeds found in space. While there is a wide range of meteoroid speeds, they normally cluster around 20 km/s, which is more than twice the speed of vehicles in low Earth orbit.

Classically there are two methods to achieve high speeds: electrostatic acceleration using high-voltage Van de Graaff generators, and acceleration by 'gas drag', in which a gas is accelerated, either by a high-pressure piston in a light-gas gun or by electric forces in plasma guns. Europe has a number of these facilities, including the light-gas gun at the Center of Studies and Activities for Space in Padua (I), the Ernst-Mach-Institut für Kurzzeitdynamik in Freiburg (D), a Van de Graaff generator of the Dust Accelerator Facility at the Max-Planck-Institut für Kernphysik in Heidelberg (D), and both devices at the Open University in Milton Keynes (UK).

While Van de Graaff accelerators can deliver a relatively large number of test particles from 0.1 mm down to some nanometres (10^{-9} m) at 1–100 km/s, they can accelerate only particles with conducting surfaces. Iron grains are traditionally fired in these machines. In contrast, light-gas and plasma guns can accelerate larger particles of any material. However, the maximum speeds are normally lower and each shot has to be prepared carefully, so not many



Laser bombardment of an aluminium sample



A crater in the HST solar cells created by meteoroid impact (left) and laser bombardment (right)

experiments can be performed in a limited time.

Van de Graaff accelerators and guns together already allow a good amount of testing. However, they are fully-fledged laboratory devices surrounded by vacuum and high-voltage systems, with the associated demand on resources.

The Laser Approach

Even high-performance lasers are now widely available and are rather benign in their demand for resources. It is therefore desirable to use them to test space materials for sensitivity against meteoroids. In order to simulate surface impacts, a green 'neodymium-doped yttrium aluminium garnet' laser, commonly referred to as a Nd:YAG laser, has been tested. Every second, the laser pulses with an energy of 30 mJ for 7 ns. This corresponds to a power of 4 MW for a very short time. A simple optical setup with two lenses focuses the laser onto a spot smaller than 0.1 mm.

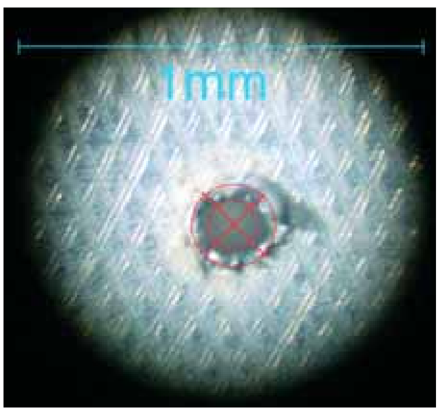
The aluminium or solar cell samples are first fixed in a holder on the optical bench. The red helium-neon guiding laser that runs parallel to the Nd:YAG beam is positioned on the target spot by adjusting the two mirrors in its path. The focusing lens is then adjusted to concentrate the laser on the target. The Nd:YAG laser then fires for the set number of shots. The whole procedure takes some 30 minutes.

Owing to the tightly focused laser creating a high energy density, the surface material is subjected to extreme thermal conditions, as in a high-speed meteoroid impact. The results are the same: the target material is evaporated (even ionised), a crater is formed and a shock expands through the material. Performing the experiments in air, the shock can be heard clearly as a click every time the laser hits the target. In the experiments at the Laboratory for Atmospheric & Space Physics (LASP), in Boulder, Colorado, USA, materials typically used in space manufacturing were laser-tested: aluminium and the composite material that makes up solar panels (using cells returned from HST in 1993). Afterwards, the materials were analysed under an optical microscope. The experiments showed that indeed the laser shots produced craters similar in shape to those from meteoroids, and that selecting the number of laser shots easily controlled the size of the crater. The empiric law is that an accumulated laser energy of 1 J created a crater 0.07 mm across; and each doubling of the laser energy increases the crater size by 17%. On average, each laser shot deepens the crater by 0.001 mm. Thus a 5 mm-deep crater normally created by a 0.5 mm meteoroid can be simulated by firing our laser 5000 times. Fortunately, the firing frequency can be set to 100 per second, so the whole procedure takes only 50 seconds.

The craters in aluminium were surrounded by white powder, which was interpreted to be aluminium oxide created by chemical reaction of the surrounding air with the hot gas. Of course, this reaction would not occur in vacuum.

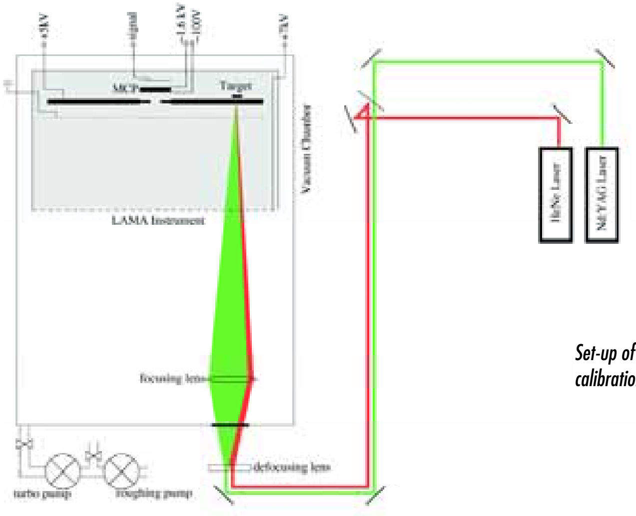
An obvious difference between meteoroid and laser craters on the solar cells is

Measuring the crater diameter in an aluminium sample



the amount of melting. This is because the low absorption of the cover glass lengthens the very brief laser shot, and the heated cell substrate (highly refractive silicon) transmits its heat to the amorphous glass. The result is a halo of melted and chemically altered material around the central hole.

Comparing the laser damage to the aluminium with that to the solar panel composite, it turns out that the craters in the composite material are about twice as deep for the same number of laser shots. This is because the shinier aluminium reflects more of the laser's power.



Set-up of the LAMA calibration experiment

Know Your Foe: Meteoroid Detectors

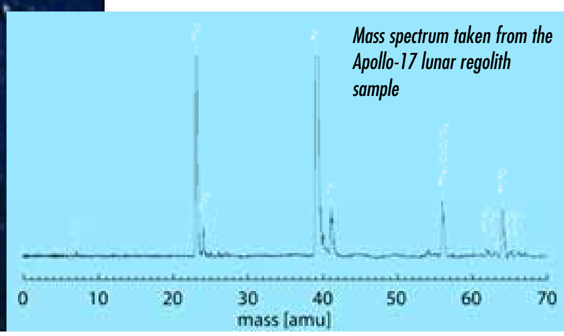
Satellites can be efficiently protected from the hazards of meteoroid impacts only if we know the number of meteoroids and their sources. Our current understanding of the meteoroid environment comes mainly from microcraters on the rocks brought back from the Moon by the Apollo astronauts, and by measuring meteoroids that enter Earth's atmosphere using highly sensitive radar equipment (*Bulletin* 113; *http://www.esa.int/esapub/bulletin/bullet113/chapter9_bul113.pdf*).

Meteoroids are also detected in space by instruments aboard satellites in geostationary and low Earth orbit. In order to improve our understanding of how many meteoroids there are and from which directions they come, more information about their sources, makeup and dynamics is needed.

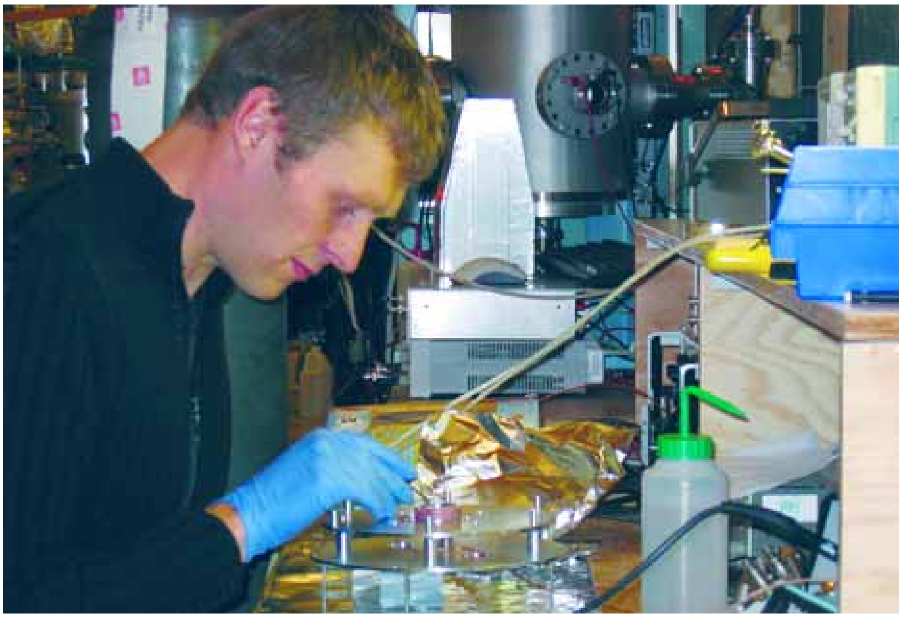
Thus, the other important application of the laser is to calibrate new instruments to detect meteoroids in space. The next generation of detectors is already working in the laboratory. One is the large-area mass analyser (LAMA), which can determine the chemical makeup of meteoroids when they hit its large (almost 1 m^2) target area. The instrument was conceived by the dust research group at the Max-Planck-Institut für Kernphysik in Heidelberg, which also developed meteoroid detectors for the Ulysses and Cassini/Huygens missions.

Because the laser shots are so similar to meteoroid impacts, the laser can be used to calibrate LAMA and to find out how meteoroids of different materials could be analysed. With LAMA, the high energy of the impact means the meteoroid is vaporised and its material is split into its chemical compounds. The impact is so energetic that the compounds are broken into individual atoms that are stripped of at least one of their electrons, making them positively charged ions. The target surface of LAMA is held at a high positive voltage (+5 kV) so that the ions are repelled

Apollo-17 astronaut Harrison Schmitt collects lunar rake samples of regolith at Taurus-Littrow in December 1972



Mass spectrum taken from the Apollo-17 lunar regolith sample



The procedure working on the LAMA instrument required some laboratory experience. Here, Markus Landgraf works on the sensitive micro-channel plate, which is at the heart of LAMA's ion detector electronics

from it. Using a careful design of the electric field inside LAMA, the ions are deflected towards an ion detector at the centre that produces an electrical pulse each time a certain species of ions hits it. Because each ion receives the same amount of energy from the electrical field inside LAMA, the ions of lighter elements like carbon or oxygen move faster than those of heavier elements like iron. The com-position of the meteoroid can then be determined by measuring the time of arrival of its compounds. We found that LAMA works equally well if the ions are created by a laser shot focused on a sample mounted on the LAMA target plate.

Meteorites recovered on Earth are made mainly of silicate minerals, such as olivine and pyroxene, and of carbon-rich material. To calibrate LAMA, metals (brass, stainless steel and lead), quartz (the simplest silicate) and graphite (the most common form of carbon) were analysed. In order to provide more realistic, astrochemically relevant materials, actual lunar regolith (dust) brought back from the Moon's Taurus-Littrow highlands by the Apollo-17 astronauts was analysed. This regolith is made up of simple silicon oxides, metal (calcium, magnesium, iron, sodium, titanium, potassium, chromium) oxides, and trace elements.

Rock samples (quartz) were ground down to powder for mixing with iso-propanol, and the mixture was inserted into the bowl-shaped sample holder. Despite the fact that the iso-propanol evaporated within a few minutes, the residual powder retained some structural strength and some adherence to the holder, so that it could even be turned upside down. This was important because some samples were coated with a thin gold layer in order to improve the electrical field directly above the sample. Once the sample was prepared, it was remounted on the target plate, LAMA was returned to the vacuum chamber, and the chamber was evacuated. Within a few hours, the optics could be adjusted and the laser switched on.

In general, the calibration experiments showed that LAMA is highly capable of distinguishing between carbonaceous material and silicates. It was found that not all of the material is broken up, but that some, especially graphite, remains in clusters of four or more atoms. The carbon clustering could be very useful when it comes to identifying organic compounds in real meteoroids. While more quantitative tests with a greater variety of materials are needed, the results so far show that LAMA can be used in space to analyse meteoroids and space debris and determine their sources.

More particularly, we have been able to identify, together with the ubiquitous contaminants sodium and potassium*, the most abundant copper and zinc isotopes in the brass sample, and the lead isotopes in the lead sample. The fact that the rather heavy lead isotopes (206, 207 and 208 atomic mass units) can still be resolved shows that LAMA can distinguish between a wide variety of chemical elements and molecules. With the Moon regolith, LAMA confirmed the very interesting abundance of titanium oxide, a chemical compound that is now being widely discussed as a good source of oxygen for future exploration missions. Singly oxidised species of all five titanium isotopes were identified.

Anti-Meteoroid Testing

The experiments at LASP provided confidence that the laser can be used for calibrating meteoroid detectors and testing meteoroid impacts on satellites and new materials at facilities in ESTEC. Such a facility requires fewer resources than a light-gas or plasma gun that are traditionally used in simulations. While a laser shot is certainly not perfectly analogous to a meteoroid impact, it is similar enough for routine testing.

Acknowledgements

The work presented here was conducted under the Douglas Marsh Fellowship awarded to the principal author by ESA in 2004. He thanks LASP for its assistance and hospitality during the project, and NASA for providing a sample of lunar dust.

esa

**sodium and potassium form ions very easily, so even minute traces of these elements, which cannot always be avoided under laboratory conditions, will show up as strong peaks in mass spectra*