wouldn't be any jobs for the Russian scientists." Success has expanded the program, which now supports 26 incubators nationwide and has funded 400 projects, about 200 of which are still in operation. All told, the heavy thrust into technology has paid off. "We're talking about billions of shekels contributed to the Israeli economy," says Edelstein.

Haim Harari. The real impact of the Soviet newcomers will come in the next generation.

Deep impact?

While Israeli science and industry are still riding this wave of new brainpower, some are beginning to consider the long-term impact of the newcomers. They have not stimulated all fields of science equally. "You don't need to do any survey to know we received, in general, very high-quality mathematicians," but newcomers have had "almost zero impact in biology," says Harari. Part of the reason for this discrepancy stems from Russia's traditional strength in the physical and theoretical sciences. Thanks to the Soviet influx, claims TAU's Amir, "Israel is now considered a superpower in mathematics." Sergei Gelfand of the American Mathematical Society agrees: The country's strong math community, he says, "is an achievement of Israeli immigration policy and practice."

Citation analysis suggests that the newcomers have lifted the overall standing of Israeli science. Over the last decade, Israeli physicists have captured a rising share of total papers published in the world's major journals, and citations per publication have been climbing, according to data compiled by the Institute for Scientific Information in Philadelphia. No clear trend could be discerned in math, although mathematicians generally take longer to publish their results and produce fewer papers on average than their colleagues in physics. "The beginning of this global influence we are starting to see only now," says Edelstein.

The new immigrants—perhaps not surprisingly—have also strengthened the country's scientific ties with colleagues in former Soviet countries. For example, the Weizmann Institute and the Landau Institute outside Moscow have established a Joint Center for Theoretical Physics on the Weizmann campus, and the prime minister's office has just established at Hebrew University a Center for Academic Ties between Israeli scientists and their counterparts in the FSU and the Baltics. In addition, Moscow space scientists last year helped a team of researchers at the Technion—14 out of 20 of whom are newcomers—locate a satellite after the Israelis had received incorrect tracking information from the United States.

In the long term, however, the jury is still out on the extent to which the Soviet immigrants will reshape Israeli science. Some newcomers stay in Israel only briefly before taking jobs abroad. "Many high-level scientists have left—here and there you find real losses," says mechanical engineer Avraham Shitzer, vice provost for research at the Technion, which has retained about 190 newcomers. But, says Harari, it's too early to say what kind of scientific talent will emerge from the students who studied science in Russian schools and are now being integrated into Israeli society. Government figures show that a third of all immigrants in the university system between 1989 and 1995 majored in mathematics and natural sciences, three times the proportion among all Israeli university students. "When you come as a 17-year-old," he says, "it's not as bad as coming as a 30-year-old who has to work as a janitor before finding a job."

"In Israel we have a philosophy that each family needs to raise a son, plant a tree, and have a house," says TAU geneticist Ben-David Yair, who came to Israel in 1973 and changed his name from Evgeny Kobyliansky to protect his family back in Moscow. "I would like to add one principle: We must also accept a new immigrant." For the most part, that philosophy seems to have taken root. "Step by step, Russian immigrants become a very important part of scientific directions, and they stop being slaves and begin to be colleagues," says Hebrew University's Khain. Adds Zadok of the Israeli Academy of Sciences, "You don't see any Ph.D.s sweeping the streets today."

–RICHARD STONE

TECHNOLOGY

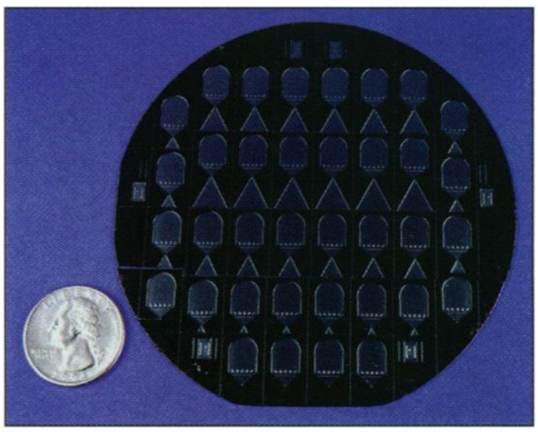
Shoebox-Sized Space Probes Take to Orbit

Technological finesse and the search for cost savings are spawning a new generation of "nanosatellites," weighing only a kilogram or so

Peter Panetta is fond of passing around a model of a satellite he's designing. That's not unusual for a NASA engineer, but what is surprising is that the model, roughly the size of a hatbox, is a full-scale spacecraft mock-up.

The cylindrical prototype, 30 centimeters in diameter and 10 centimeters tall, represents a conceptual design for the first of NASA's nanosatellites—spacecraft with total launch masses of between 1 and 10 kilograms, or a mere one-thousandth the mass of a conventional satellite. A hundred or more of these tiny spacecraft, at a cost of half a million dollars apiece, will swarm through the magnetic fields and trapped particles near Earth during NASA's Magnetospheric Constellation (MC) mission, planned for 2007. Other NASA nanosatellites may soon hitchhike to Mercury on a macrosatellite, carry crystal-growth experiments in low Earth orbits, or fly in formation to study Earth's atmosphere from above.

These pint-sized satellites are the offspring of two converging trends: NASA's effort to develop faster and cheaper alternatives to the billion-dollar space science



Mighty mites. Tiny thrusters carved from silicon.

missions of the 1970s and '80s, and the promise of microelectronics and microfabrication for shrinking spacecraft parts, including sensors, power supplies, and even thrusters. The first nanosatellite has not yet flown, but NASA managers are confident that within 5 years, the technologies will be

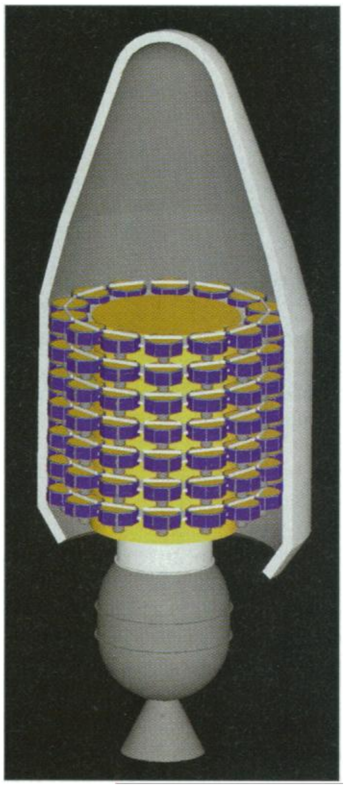
CREDITS: (TOP TO BOTTOM) MUTSUMI STONE; (BOTTOM) WILHELMUS DEGROOT/JOHN H. GLENN RESEARCH CENTER AT LEWIS FIELD mature enough for the MC mission and, ultimately, for swarms of other nanoprobes.

"Miniaturization is going to be pervasive in all of our spacecraft," says Richard Vondrak, head of the Laboratory for Extraterrestrial Physics at NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. "We hope to launch them on smaller launch vehicles, do it with fewer dollars, or put up more of them." As a result, says one enthusiast, Rick Fleeter, who is the founder and CEO of AeroAstro in Herndon, Virginia, "scientists will be able to dabble in space research in the same way they now dabble in terrestrial laboratories."

Panetta, who is the manager of NASA's nanosatellite technology program at GSFC, is drawing on a range of technologies to shrink satellites for the MC mission and its successors. Microelectronics will reduce the size and power consumption of data processing and communications systems, moldable batteries will be packed into the odd spaces that would otherwise remain empty, and miniaturized machines—micro-electromechanical systems (MEMS), in engineering jargon—will replace bulky mechanical systems with light, silicon-based equivalents.

A dime-sized thruster, currently under development at NASA's John H. Glenn Research Center at Lewis Field in Cleveland, Ohio (formerly NASA's Lewis Research Center), is a startling example of one MEMS device Panetta's group is studying. Each tiny thruster consists of a combustion chamber and nozzle etched into silicon. To eliminate the complex fuel-delivery systems of larger rocket engines, NASA engineers made each thruster a self-contained unit. Each carries a single burst of fuel sealed in its combustion chamber, and after ignition—possibly by diode lasers—it is discarded. At about a gram each, nanosatellites could carry hundreds of these thrusters for attitude control. Panetta believes MEMS thrusters will be perfected in time to be incorporated in the MC nanosatellites.

Just downsizing larger systems won't be enough, however; miniaturized spacecraft will face some new demands. The output of the solar cell arrays that produce spacecraft power will fall to just a few watts as they shrink. With such meager power budgets, individual spacecraft subsystems must run at a half-watt or less each, roughly a fiftieth the power consumption of many conventional equivalents. As a result, nanosatellites like the MC probes, which will follow orbits taking them far from Earth, will often be beyond range of their miniaturized communication systems, putting a special premium on spacecraft self-reliance. The nanoprobes will have to collect data and make orbital adjustments autonomously; only when they pass close to Earth will they be able to download memory and receive new mission objectives.



Satellite swarm. A hundred or more nanosatellites, each 30 centimeters in diameter, will ride a single rocket into orbit, then disperse to study the magnetosphere.

CREDIT: PETER PANETTA/GSFC

The payoff, in the MC mission, will be a far more comprehensive picture of the magnetosphere—a vast, teardrop-shaped region of magnetic fields and ions surrounding Earth—than one or several conventional satellites can provide. The magnetosphere is so variable and turbulent that isolated measurements cannot capture its full complexity. As MC mission program scientist Thomas Moore of GSFC puts it, "Most of what we've done up until now has been akin to trying to understand severe storm development in the Midwest by driving around in a car with one rain gauge and a thermometer hanging out the window."

The MC mission, currently funded at a total cost of $120 million including launch costs, will create the orbital equivalent of a terrestrial weather station network. The swarm of 100 or more probes will be packed into the payload bay of a single Delta rocket; once in space, each nanosatellite will fire a miniature propulsion system to reach its final orbit. The current plan is to place the satellites in equatorial orbits with perigees of about 20,000 kilometers and various apogees of up to half a million kilometers. The spacecraft will sample the magnetosphere with magnetometers and charged particle detectors and then download their data to ground-based computers during their closest approaches to Earth.

The MC mission will yield time-lapse photographs of the magnetosphere, with each nanosatellite providing one pixel of data. "That's the kind of thing you could not do without a constellation of satellites, and you couldn't build big satellites to do it because you couldn't afford to," says Dave Akin, director of the University of Maryland's Space Systems Laboratory. The ability to monitor conditions throughout the magnetosphere, space physicists hope, will let them trace turbulence stirred by the wind of particles blowing from the sun and follow the growth of electromagnetic disturbances known as substorms, which can affect satellites and ground-based communication systems.

Other nanosatellites may also fly in the next decade. NASA is considering piggybacking a trio of nanospacecraft on the Janus Pathfinder probe to Mercury, which, if approved, could be launched as early as 2005. The mother ship would release the nanoprobes near Mercury in trajectories that would carry them through different regions of the planet's magnetosphere. And AeroAstro is developing a 1-kilogram satellite, Bitsy, that is meant as an inexpensive alternative to booking space on a space shuttle or the international space station.

Bitsy would provide basic accommodations—power, attitude control, and communications—for experiments in low Earth orbits, such as crystal growth studies, downward-looking Earth science observations, or anything else an imaginative scientist can come up with. And it comes with a bargain-basement price, which AeroAstro estimates at $50,000 to $100,000 per satellite. To keep launch expenses down, Bitsy satellites will probably hitch rides to low Earth orbits in unoccupied space aboard NASA or European Space Agency rockets.

Nanosatellites won't fill every niche in space science, says Akin. "There are people, I'm not one of them, who will tell you everything could be done with microsats." There will always be a need for satellites that carry inherently large systems such as optical telescopes and other sensors, he says.

Panetta agrees, but he can't help musing about truly Lilliputian spacecraft. "If you really want to think far reaching, there's the possibility of a femtosatellite," essentially a solid-state satellite on a chip, weighing 100 grams or less, and about the size of a credit card. For now, he must be content with the nanosatellite that takes up nearly half the surface of a desk in his office.

–JAMES R. RIORDON

James R. Riordon is a science writer in Greenbelt, Maryland.