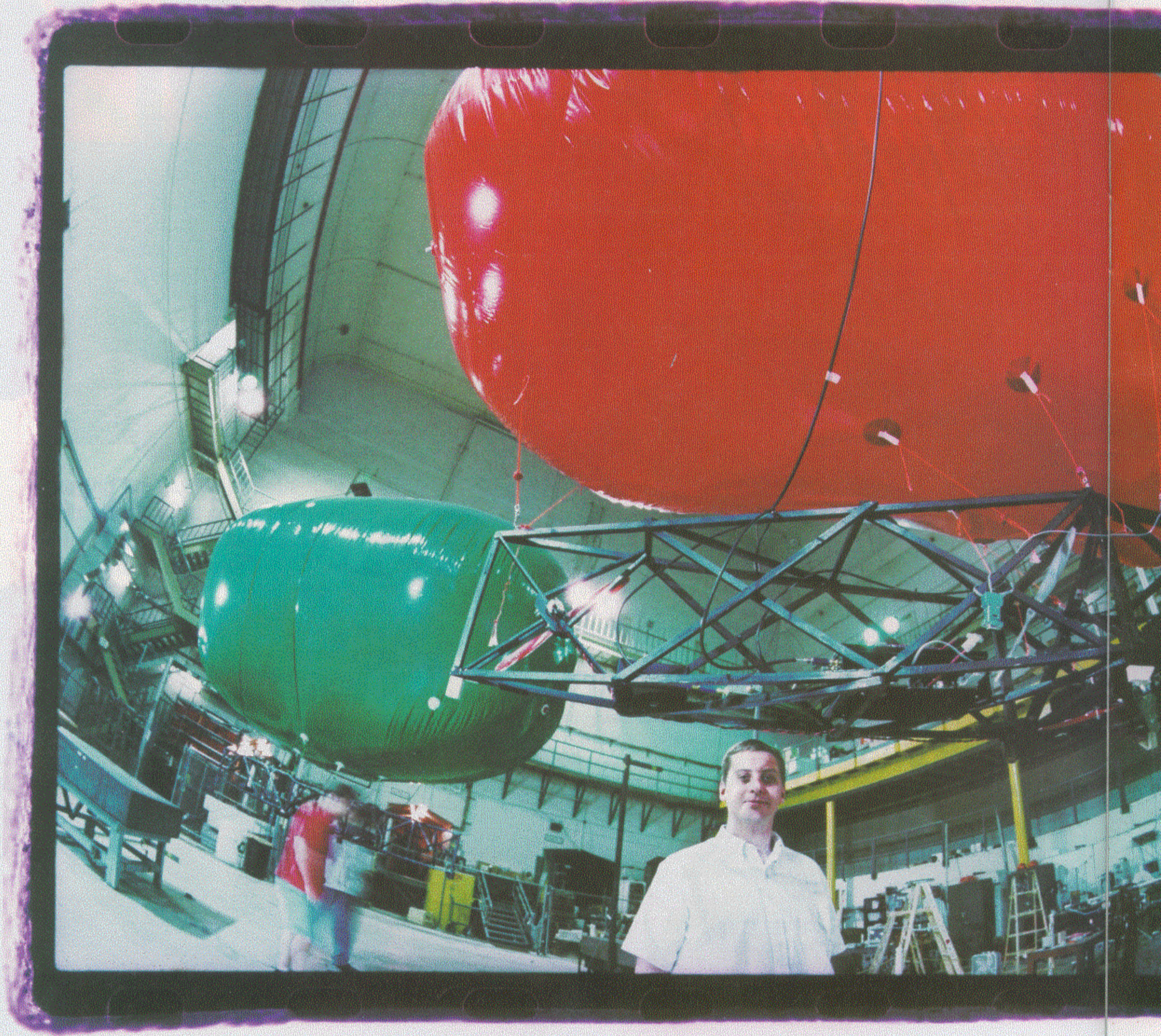


Follow my leader

Why build giant space telescopes when a few small spacecraft flying in formation could do a better job for a fraction of the cost? Catherine Zandonella reports

IN A large hangar known as End Station 3, sunk half underground at Stanford University in California, a giant green beast rises, turns slowly and lumbers off into the cavernous room. A second beast, this one bright red, noses the air as if it is detecting a scent, and then follows its companion.

These beasts, in reality plastic blimps the size of pick-up trucks, are the creations of aerospace researcher Jonathan How. As they float through the hangar, it soon

Balloon ballet: aerospace researcher Jonathan How and the blimps he is teaching to fly in formation

Photography: Anne Hamersky

becomes clear that the green blimp is in charge. When it stops, so does the red one. When the green blimp turns, the red one follows suit, in a giant game of copycat.

Although they might seem clumsy, the blimps are performing a complex task: formation flying. This is difficult enough with a human at the controls but these blimps are flying without any help from How or his colleagues. And what blimps are doing today, spacecraft will be doing tomorrow. How and a growing number of aerospace researchers believe that formation flying will revolutionise space exploration. The technique allows scientists to combine the measurements from several spacecraft in way that creates telescopes and sensors of unprecedented size and power, and at an affordable price.

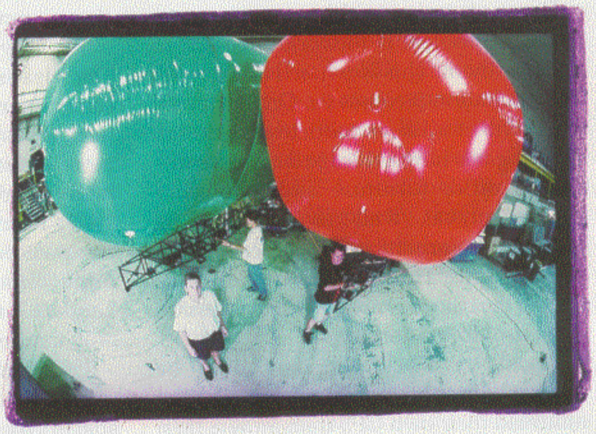
NASA is already designing such a telescope to look for Earth-like planets around other stars. Its resolution will be hundreds of times that of Hubble but it will cost only a fraction as much. Meanwhile, the US Air Force is building a fleet of radar-imaging satellites that will spy on objects on Earth. It's all part of the trend towards smaller, cheaper and more flexible space exploration vehicles. But before any of this will be possible scientists must perfect the techniques of flying in formation and this is far from easy.

The basic challenges are well understood. The spacecraft must be able to determine their location as well as the locations of the other spacecraft in the fleet. They must be able to calculate their flight paths and decide whether they are drifting apart. If any adjustments are necessary, they must be able to work them out without help from the ground. All this must be done using as little fuel as possible and in a way that minimises the amount of processing and communications between the craft.

Keeping the spacecraft in formation, however, is tough. Orbiting spacecraft tend to drift off-course because of such factors as atmospheric drag, the solar wind and, the biggest problem of all, the non-spherical shape of the Earth. But in the past few years, scientists have worked on finding a set of individual orbits that will naturally maintain the spacecraft in the vicinity of each other. For spacecraft orbiting the Earth, it turns out that there is a special set of elliptical orbits, called Hill's orbits, that meets this condition. While Hill's orbits have long been used for rendezvous and docking in space, it was only earlier this year that David Miller at the Massachusetts Institute of Technology and his colleagues at Texas A&M University realised they could be used for formation flying. "If you want to do formation flying, you have to accept the constraints that nature puts on you," says Miller.

The reason Hill's orbits can be used is that the three-dimensional shape of a formation is not important when observing the Earth from space. Rather, the crucial factor is the projection of the formation onto the Earth's surface, that is, the way the formation would appear to somebody on the surface looking up into space. As long as this doesn't change, the formation can function as a telescope or radar imaging array. One property of these orbits is that the formation rotates slowly during each orbit.

Since Miller calculates Hill's orbits by assuming the Earth is spherical, the spacecraft still need to correct their orbits to cope with the Earth's real shape. But the amount of correction is far less than in other orbits. Indeed, without these fuel-saving orbits, the satellites would have to carry so much fuel that formation flying would not be feasible. "That is the breakthrough that has allowed formation flying to go through," says Alok Das of the



US Air Force's Space Vehicle Directorate at Kirtland Air Force Base in New Mexico.

Outside the gravitational influence of the planets, in deep space, orbital effects are much less of a problem but fuel efficiency is still an issue. "The question is, what are the most efficient ways of rearranging the formation with the least amount of fuel," says Paul Wang at the University of California, Los Angeles. Wang is developing ways of changing formation that are reminiscent of the way the members of a marching band move to change direction without bumping into each other.

None of these complex manoeuvres will be possible, however, if spacecraft cannot measure their position and attitude. "People had proposed formation flying in the past," says Frank Bauer, who heads the Guidance, Navigation, and Control Facility at NASA's Goddard Space Flight Center, "but you really can't do it until you have a navigational sensor. That's where GPS comes in."

Constellations in orbit

The Global Positioning System, set up by the US Department of Defense, consists of 24 NAVSTAR satellites that circle 20 200 kilometres above the Earth. Each satellite transmits a code that can be picked up by portable receivers on Earth. These receivers use highly accurate clocks to measure the signal's travel time and hence the satellite's distance. By comparing the distance to three or more of the satellites, and with the help of a few tricks, the receivers can determine their location to within a few centimetres.

This system also works in orbit, and has already been used to help uncrewed spacecraft rendezvous and dock. "For the most part, GPS is there for people on Earth. We've adopted it for space," says Bauer.

Given accurate position measurements, the next problem is to work out what to do with them. This is where How's work in End Station 3 comes in. Once a terminal point in a linear particle accelerator, the hangar is now a storage facility for discarded office furniture and laboratory equipment, as well as the proving grounds for formation flying. Beneath the yellow lights, How and his students are testing the computer algorithms necessary to control formation flying.

Since NAVSTAR signals cannot be received indoors, How's colleagues have mounted their own GPS transmitters high up on the hangar walls. On each blimp they hung a wooden basket containing a GPS receiver, a circuit board, batteries, and motors that crank the blimp's propellers. Each blimp monitors the signals and broadcasts its position and attitude to a central computer. The computer monitors changes in the green blimp's position, calculates how the red blimp should move to maintain the required formation and sends it the required directions. In future, this processing will be done onboard but the result will be the same.

"Blimps are perfect for testing the control problems in formation flying," explains How, who thought of using blimps when he attended a hockey game and saw a large blimp travelling around inside the arena, dropping T-shirts on the fans. "They are relatively inexpensive and can be rigged fairly easily to carry GPS receivers."

Using GPS indoors, however, is not easy because the signals bounce off walls and equipment, creating reflections that confuse the receivers. So How plans to continue his experiments outside with a small fleet of toy trucks. The lead truck will be controlled via radio remote control, while three other trucks will use GPS to find the leader and follow it around in formation.

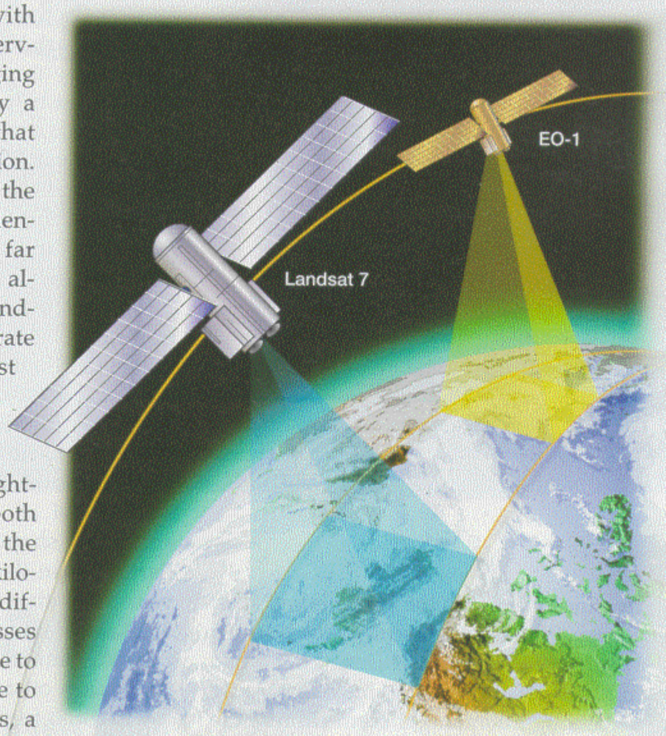
The lessons learnt from the blimps and trucks will soon be put to use in space. How and his students are taking part in a project to build three satellites the size of milk crates that will fly in formation sometime in 2001. The project is part of the University Nanosatellite Program sponsored by the US Department of Defense, NASA and industry partners.

In the meantime, the first demonstration of semi-autonomous formation flying in orbit is slated for December this year with the launch of Earth Observing (EO-1), a land-imaging satellite that will carry a cheap new camera that offers very high resolution. The idea is to compare the camera's images with identical shots taken by a far more expensive camera already in orbit aboard Landsat 7. To make an accurate comparison, EO-1 must orbit directly behind Landsat 7, trailing by only a minute or so.

This task is not straightforward. Although both spacecraft will be in the same orbit, roughly 700 kilometres overhead, their different shapes and masses means that EO-1 will have to adjust its orbit from time to time. To accomplish this, a ground station will measure Landsat 7's position and broadcast this information to EO-1, which will be taking GPS measurements of its own position. EO-1 will then calculate the future orbits of both spacecraft. If they match, the spacecraft does nothing. But if its future path deviates from Landsat 7's, the onboard computer will work out a manoeuvre to put it back on track, says David Folta at Goddard, who heads the EO-1 project.

While the EO-1 mission qualifies as formation flying, the fact that the ground is involved means it is still a long way from the completely autonomous missions that NASA envisions. Space scientists talk of achieving a "lights out" mode, where ground controllers can supervise the first stages of a mission, then turn off the lights in the control room and go home, leaving the spacecraft to perform on their own.

This is the kind of autonomy demanded by a NASA project called Space Technology 3 being developed at the Jet Propulsion Laboratory in Pasadena, California. Due for launch in 2003, ST3 will combine the images from two small telescopes flying in formation to produce images almost as good as those of a very expensive giant telescope. Two collector spacecraft will reflect light into a third instrument where the two beams are combined. The interference pattern created will then be processed to produce an image of the



Follow that satellite: EO-1 will maintain a careful orbit 1 minute behind Landsat 7 so that their images of the ground can be compared

Orbital dynamics: without special fuel-saving orbits, formation flying wouldn't be feasible

object that generated the light.

A space-based interferometer with a baseline distance of 200 metres between collectors would have a resolution 800 times better than that of the Hubble Space Telescope. With this increased capability, scientists will be able to look for new stars, planets around other stars and black holes.

The problem is to maintain formation while flying several million kilometres from Earth. Since the spacecraft will not orbit the Earth but will fly in deep space, orbiting the Sun, they cannot rely on the NAVSTAR GPS signals. Instead, the spacecraft will carry GPS transmitters, creating their own mini-GPS constellation. "Each spacecraft is like a NAVSTAR satellite to the other spacecraft in the group," says Kenneth Lau, the key architect of JPL's Autonomous Formation Flying system. This will be accurate to within a few centimetres. A more specialised system will then fine-tune the spacecrafts' positions to within a billionth of a metre—a feat that can be achieved using laser measurements and fine positional corrections.

All this has to be done without any help from Earth. When devising autonomous control algorithms, a key design question is which spacecraft gets to be the boss. There are two basic types of control architectures. One is a centralised master-slave arrangement, where the lead spacecraft detects the locations of all follower spacecraft and sends them instructions on how to manoeuvre.

The second is a decentralised system, in which the lead spacecraft sends out instructions but leaves it to the followers to calculate their own positions and determine how to move to stay in formation. In this scenario, each spacecraft could take turns being the leader, similar to the alternation of leaders in a flock of flying birds. Each spacecraft carries the necessary equipment to lead, making the system far more versatile, but also more complex and more expensive. "The best approach might be to switch from centralised to decentralised control depending on the application," says Lau.

'The mission will look for ripples in space that are produced when black holes collapse'

With either of these control mechanisms spacecraft can change position and damaged craft can be taken out of service and replaced. "Before, we had to build huge platforms for sensors and other equipment. Now, we will be able to update specific pieces of equipment with new technology—we don't have to do it all at once," says Fred Hadaegh, director of JPL's formation flying programme. "Formation flying is an incredibly powerful tool for doing distributed communications, sensing, and telemetry." He envisions an armada of spacecraft each carrying a different scientific instrument that can be swapped in and out depending on the mission.

Flying spies

Autonomous formation flying will also be used for spying. The US Air Force is developing a GPS-controlled fleet of spacecraft called TechSat 21 that will use synthetic aperture radar to spot moving objects on the ground. Fleets of spacecraft provide much greater flexibility than a single craft, says Das. "You can actually do several jobs with the same equipment," he says.

When looking for moving objects, for example, the ideal spacing between the spacecraft is about 500 metres. But when pinpointing signals on the ground, the ideal baseline is several kilometres. "So you command just one of them to drift back. When the job is done, you move the satellite back to the cluster," Das says.

The Techsat 21 system will be able to decide for itself what formation to adopt based on the tasks it is asked to carry out. The first few satellites are due to be launched late in 2003.

The list of missions involving formation flying continues to grow. The European Space Agency plans to start its own formation flying programme this year. It has long wanted to build a giant interferometer using spacecraft separated by distances many times larger than that between the Earth and the Moon. The mission, called LISA, will look for ripples in space called gravity waves that are produced when black holes collapse and neutrons stars collide (*New Scientist*, 10 August 1996, p 36). Gravity waves have never been detected directly, and doing so could open up a whole new branch of astronomy. And earlier this year, NASA announced plans to study interactions between the Earth's magnetosphere and the solar wind by making simultaneous measurements over huge volumes of space.

Once the technical challenges are worked out, NASA researchers are confident that autonomous formation flying will revolutionise the way we explore space. And for this, they will have the lumbering ballet of a few giant blimps to thank. □

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