COMMENT

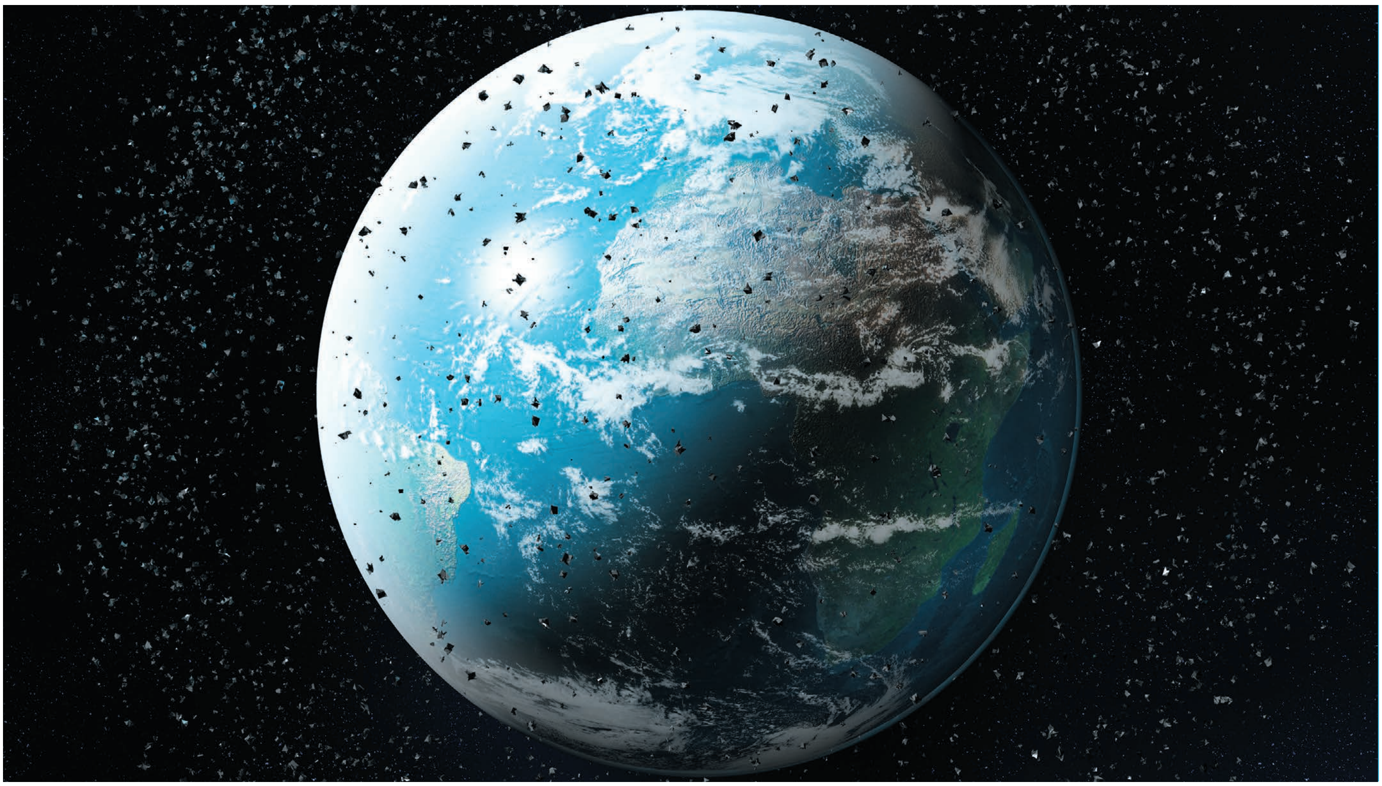
HISTORY Did Einstein's first wife, Mileva Marić, influence his science? **p.28**

PUBLIC HEALTH The long road to ridding the world of leprosy **p.30**

CITIZEN SCIENCE Thousands of high-school students discover ten new bacteria **p.31**

OBITUARY Manfred Eigen, observer of fast reactions, remembered **p.32**

MACIEJ FROLOW/GETTY



A cloud of satellites and space debris orbits Earth, as seen in this artist's impression.

Four steps to global management of space traffic

Jamie Morin sets out the elements required to track satellites and avoid crashes.

Space is getting crowded. Today, we can track more than 20,000 artificial objects that orbit Earth — including 1,500 working satellites and a plethora of expired craft, used boosters and other debris. That's just the tip of the iceberg. Later this year, ten times as many objects could be revealed when the US Air Force switches on its Space Fence (see go.nature.com/2dxztu3). This powerful radar, located on Kwajalein Atoll in the Pacific Ocean and costing US$1.6 billion, will make 1 million observations a day.

Keeping up with space traffic is becoming more challenging. Satellites are getting smaller and cheaper to launch. Scientists, companies and even schools can build one to photograph Earth for as little as $10,000. And constellations of thousands of spacecraft will increasingly be used for ambitious projects. For example, the company SpaceX in Hawthorne, California, aims to launch nearly 12,000 small satellites to form a space-based internet system by the mid-2020s.

The potential for collisions, accidents, misunderstandings and conflicts is growing. Each crash releases debris that threatens other space activities. In 2007, China's test of an apparent anti-satellite weapon created tens of thousands of shards and raised geopolitical concerns (see go.nature.com/2tv2nja). In 2012, the crew of the International Space Station was forced to shelter in the Soyuz escape capsules when debris from a 2009 satellite collision passed close by.

To adapt to a crowded and democratized space future, we will need some form of space traffic management. The US government is seeking to lead global efforts while developing policies to manage its satellites more effectively. This would not involve 'traffic police' directing satellites left or right, but a system more like the weather service (see go.nature.com/2dtjznn). Satellite operators would share information and receive status reports and collision ▶

alerts. Companies would develop and sell services and apps based on the data.

But space traffic is a global concern, affecting civil, commercial and national security activities. China and India are now major players; Australia and New Zealand have both created national space agencies in the past three years. Entrepreneurs and educators are eager to expand their foothold. Legally, they have every right. The 1967 Outer Space Treaty states that no country may restrict another's access to and peaceful use of space.

But there are few internationally accepted rules or norms for operating in orbit. Discussions have occurred intermittently, including around the European Union's draft Code of Conduct for Outer Space Activities, and in the United Nations Committee on the Peaceful Uses of Outer Space. But no global framework exists for coordinating spacecraft movements.

An international regime for managing space traffic could in some ways mirror that for aviation: multilateral standards and practices for safety and communications, augmented by bilateral agreements covering certain economic activities and safety situations. But there are major differences between the control of space and of air traffic. Unlike most aircraft, satellites are not required to transmit their identification, speed, direction or altitude. Establishing ownership is hard. The positions of craft are uncertain and some of the best data are kept private for commercial or governmental reasons. Expired satellites and debris can remain in orbit and go uncontrolled for centuries.

Here, I outline the four main elements of a global management system for space traffic, and the steps needed to make it happen.

FOUR ELEMENTS

Improved tracking. Aeroplanes are controlled much more strictly than satellites are. Air-traffic systems direct aircraft along registered flight paths during trips that are measured in hours. Most aircraft broadcast their positions continuously. The United States uses 150 radars to follow 5,000 planes at peak times over its territory[1]. By contrast, just a few dozen sites worldwide track tens of thousands of space objects. Satellites can be left for years to follow orbits that are defined only by the laws of physics.

Tracking space objects is technically difficult, especially if they are small and fast-moving. Objects can be as small as a fleck of paint or as big as a city bus (see 'Traffic jam'). And most travel many kilometres each second, along orbits from 200 kilometres to 40,000 kilometres above Earth's surface. Currently, the US military uses a website to publish extensive data for objects that are larger than about 10 centimetres (www.space-track.org). However, for every tracked object, there are 20–30 times as many pieces of debris. Most are too small to be followed, but many could end a mission if they were to hit a satellite.

Placing a greater number of improved sensors in more locations around the globe would increase the frequency and sensitivity of measurements. This will become more important as satellites manoeuvre more often to change their orbits. Better still, real-time information from on-board sensors and communications links can be shared by space operators — as they are for aircraft. Sharing such information will be crucial as satellite operations become more automated. Finally, fitting satellites with transponders that are designed to transmit position even after a satellite fails could provide precise location information and reduce false collision alarms.

Ultimately, global sharing of tracking data is desirable, to make the best use of sensors around the globe. Within the next few years, national systems could complement the US Space Fence. These could be operated jointly with US programmes through bilateral and multilateral data-sharing agreements, such as those now used by the US Air Force's Combined Space Operations Center at Vandenberg Air Force Base in California, to share tracking and collision-warning information with other countries and companies.

"Expired satellites and debris can remain in orbit and go uncontrolled for centuries."

The private sector should also contribute. Associations of satellite operators could provide tracking data and plans for craft manoeuvres, and companies that estimate satellite positions could enable the use of their commercial tracking data. Increasingly, private companies are eager to sell space-traffic data and value-added services to satellite operators. The prospects for international cooperation on tracking and management are constrained by geopolitical risks, in that some countries might not want to rely on the United States and would seek their own, independent data. This is analogous to the current situation with global navigation and timing data, in which Russia, European nations, China and Japan have all developed some form of alternative to the US-operated Global Positioning System.

Prediction and identification. To forecast collisions, orbits need to be predicted accurately. Sparse observations make determining a satellite's location and velocity uncertain. So, too, do limitations in models of gravity and other forces, such as drag from the upper atmosphere.

Possible collisions can be forecast using models when 'bubbles' of uncertainty overlap. Because of the large uncertainties, most possible collisions will not result in an actual crash: given the population of satellites currently in orbit, only one or two such collisions are currently expected to occur each decade[2]. But satellite owners need to assess the risks. Manoeuvring a satellite is not taken lightly — it consumes fuel, creates other collision risks, might interrupt the satellite's mission and can reduce its useful lifespan. Missions need to establish thresholds of probability for collision alerts, balancing the frequency of manoeuvres with acceptable risks.

Operators also need to be identified. Ownership is much harder to establish today than it was when few nations operated in space. Under the UN Convention on Registration of Objects Launched into Outer Space, governments are obliged to record new space objects. But this takes weeks or months, and lists are incomplete. One rocket can launch dozens of satellites, and some satellites carry smaller ones inside them[3]. Responsibility for small pieces of debris that have not been tracked consistently is especially hard to pin down.

As the numbers of craft and operators grow, precision tracking and manoeuvre information will need to be provided quickly and completely. For example, in-orbit maintenance systems would need near-real-time information to avoid collisions with other satellites.

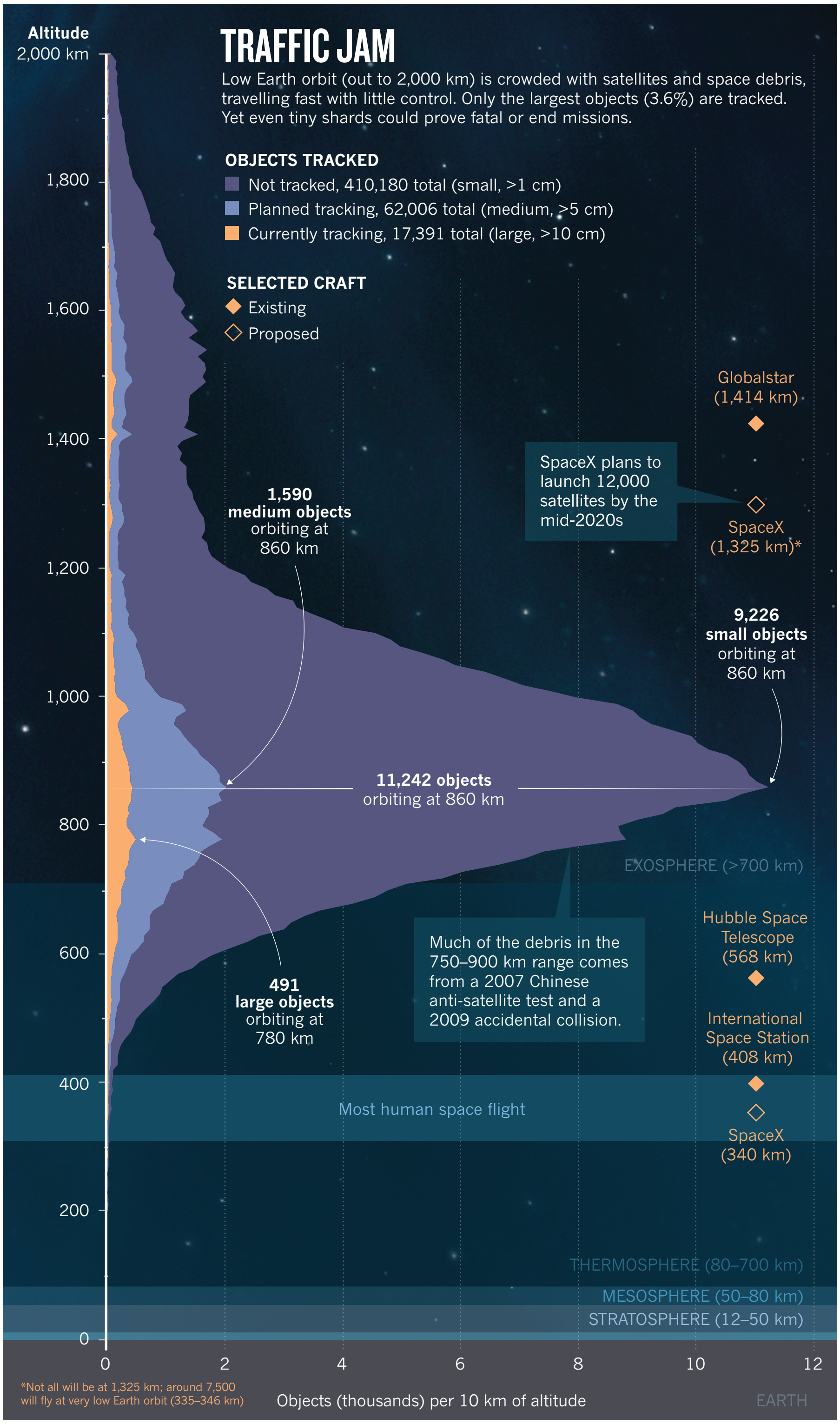
Governments and companies such as ExoAnalytic Solutions in Foothill Ranch, California, and LeoLabs in Menlo Park, California, are developing services for reporting potential collisions; currently, the US Air Force is the primary provider. To be relevant, these services must be available 24 hours a day and be updated rapidly and regularly. They must also handle contradictory data from multiple sources effectively.

Standards and norms. Data-sharing protocols, standards and norms for operating in orbit and mitigating debris need to be developed and agreed internationally. In an April 2018 speech, US vice-president Michael Pence announced that the Department of Commerce will take a lead in establishing common global practices to manage space traffic. However, many more steps are needed for successful implementation[4].

To build global consensus, the US government must consult with commercial space actors and international partners. For example, an industry–government forum of space experts is being established by the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS).

Concerns will need to be ironed out regarding handling of proprietary and sensitive information, lines of management authority, distribution of development contracts and the potential for liability.

Voluntary standards and economic incentives for compliance would be a good first step. For example, the World Economic Forum is building an industry coalition along these lines. It has sought proposals for setting up a Space Sustainability Rating



SOURCES: SPACE-TRACK.ORG/THE AEROSPACE CORPORATION

system, modelled on the approach used to certify green buildings.

Reduce space debris. Most of the current collision threat to active satellites is from debris rather than from other satellites. To maintain a sustainable orbital environment for the long term, the creation of further debris must be limited. International guidelines on space-debris mitigation should build on those drafted by the Inter-Agency Space Debris Coordination Committee (IADC), a group of 13 civil space agencies[5]. For example, the IADC's '25-year rule' calls for satellites in low Earth orbit to be removed within 25 years of the end of their mission. Eliminating all on-board energy sources — from fuels to spinning momentum wheels — lowers the risk of decommissioned satellites exploding. Some especially hazardous debris objects might be removed from orbit, if technology, policy and economic barriers can be overcome.

The US Federal Communications Commission, which is charged with licensing all US commercial communications satellites before they are launched, has announced that it will update its rules on debris mitigation (see go.nature.com/2einkjh). Encouraging other nations to create or enhance their national rules and standards will improve the space environment, even without international treaties.

WHAT NEXT?

The United States is beginning to take the first steps. The federal government has plans to move space-tracking data from the military to a civil agency. This could increase international public trust and willingness to share data, and could improve space safety. Relationships remain to be built across US government agencies, between the public and private sectors, and between space-capable countries. Shifting duties to different federal departments and handing tasks to contractors will not be enough to protect valuable space assets.

Dozens of data-sharing arrangements between the US government, foreign government agencies and commercial satellite operators need to be linked. Data formats must be compatible, and protocols will be needed for merging streams of data containing proprietary or national-security information.

National and international norms and standards of operations must be agreed. Discussions have been under way for years; as space traffic escalates, now is the time to accelerate progress domestically and globally. The International Astronautical Congress meeting in Washington DC this October will be a key opportunity that should not be missed. ■

Jamie Morin *is executive director of the Center for Space Policy and Strategy at The Aerospace Corporation in Arlington, Virginia, USA, which runs a federally funded research and development centre in support of the US space enterprise. He is a member of the World Economic Forum's Global Futures Council on Space Technology, and previously served in the US Department of Defense.*
e-mail: jamie.morin@aero.org

1. Federal Aviation Administration. *Air Traffic by the Numbers* (FAA, 2018).
2. Inter-Agency Space Debris Coordination Committee. *Stability of the Future LEO Environment* IADC-12-08, Rev. 1, January 2013 (IADC, 2013).
3. McLeary, P. 'Space Mystery: Are Russian Doll Sats a Threat?' *Breaking Defense* (16 August 2018).
4. Gleason, M. P. & Cottom, T. *U.S. Space Traffic Management: Best Practices, Guidelines, Standards and International Considerations* (The Aerospace Corporation, 2018).
5. Inter-Agency Space Debris Coordination Committee. *IADC Space Debris Mitigation Guidelines* IADC-02-01, Revision 1, September 2007 (IADC, 2007).

J.M. declares competing financial interests; see go.nature.com/2tpncjt for details.

CLARIFICATION

In the Comment 'Four steps to global management of space traffic' (*Nature* **567**, 25–27; 2019), the graphic 'Traffic jam' originally implied that all 12,000 SpaceX satellites will orbit at 1,325 km; in fact, around 7,500 of them will fly at very low Earth orbit (340 km).